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This report discusses new tropical cyclone research being conducted at Colorado State University, research which may be used as background information by tropical cyclone forecasters. Observational findings and speculations from a recent research project are presented, addressing: (1) various climatological characteristics of tropical cyclones; (2) tropical cyclone formation; (3) tropical cyclone structural variability; (4) tropical cyclone intensity change; and (5) tropical cyclone outer radius wind distribution.

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REMARKS (*Continue on reverse*)

Enclosure (1) discusses tropical cyclone research projects being conducted at Colorado State University. Results of this research can be used as background information by tropical cyclone forecasters.

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RECENT COLORADO STATE UNIVERSITY TROPICAL CYCLONE RESEARCH OF INTEREST TO FORECASTERS

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Colorado State University
Fort Collins, CO 80523

TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

1. Introduction

Tropical cyclones have been a subject of meteorological concern to the US Navy since its inception. Because of the severe data limitations which exist over the tropical oceans, a documentation of the varying structures and physical processes occurring in these types of storm systems has been difficult to obtain. To quantitatively measure the wind, height, temperature, and moisture fields occurring at all levels within tropical cyclones, one is required to resort to averaging many years of upper-air soundings around these cyclones. It is necessary that the data from tropical cyclones having different structure, motion, and behavioral characteristics be separately stratified and compared. This is known as the rawinsonde compositing approach. Our project has made extensive use of this research methodology for the last decade and a half. We are now also performing individual case analyses of the Guam aircraft reconnaissance flights into tropical cyclones.

Despite recent-year knowledge gains about tropical cyclones, the author believes that a large potential exists for improving our understanding and forecasting of Far East tropical cyclones if we make the necessary efforts to perform detailed analyses of all of the many years of data which are available around these storms. This requires the processing and compositing of many thousands of upper air and aircraft reports about several hundred cyclones at many different time periods, which is possible through extensive use of composite analysis techniques. Theoretical and observational inferences drawn from such multi-source data can lead to forecast improvement.

The information presented in this paper has made use of our project's 21-year (1957-1977) rawinsonde data sets from the western

North Pacific (Fig. 1.1) and our project's recent analysis of three years (1980-1982) of western North Pacific Air Force weather reconnaissance flights into tropical cyclones. These data sets and the software programs to handle them have taken a number of years to develop. The author believes that they represent a new source of observational information about the tropical cyclone and allow for physical insights into the processes occurring within these storms which would not otherwise be possible.

The following chapters discuss some of the new research results which have been obtained from these data sets relevant to the questions of tropical cyclone climatology, formation, structure, intensity change, and outer radius wind distribution. It is hoped that these data, and the physical inferences which have been drawn, will provide some useful background information to the tropical cyclone forecaster.

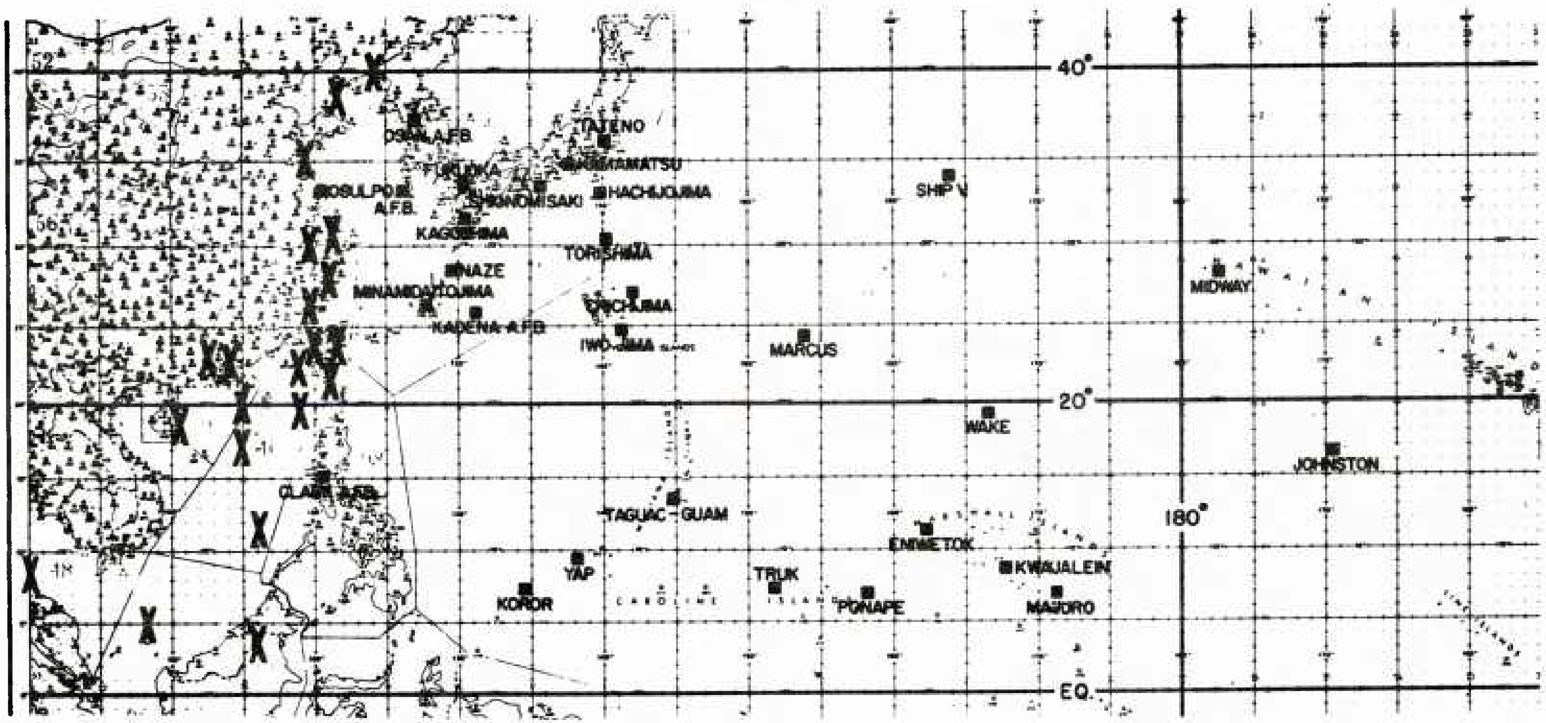

Fig. 1.1. Map showing the locations of the 48 rawinsonde stations contained in our northwest Pacific data set for the 21-year period of 1957-1977 (solid boxes). The X's show the Asian upper-air stations we have incorporated into our upper-air network. Each of these latter stations have data for a 10-20 year period.

2. Climatological Characteristics

a. Global Statistics

There are approximately 80 tropical cyclones of maximum sustained winds of 17 m/s (39 mph or 34 knots) or greater which occur over the globe per year. This is the usual international criterion for a named or numbered tropical cyclone. Figure 2.1 shows the location of the initial detection points of such tropical cyclone formation for a 20-year period. About half to two-thirds of these cyclones reach hurricane intensity (maximum sustained winds $\geq$ 32 m/s, 73 mph or 64 knots). As shown by Table 2.1, the annual percentage variation in the global number of tropical cyclones over the last 27 years has ranged from -16% to +22%. The average annual variation is only 7 percent which, considering the often large individual ocean basin variation of cyclones, is quite small.

About 13% of the globe's tropical cyclones form poleward of 20° latitude and nearly all of these occur in the Northern Hemisphere (N.H.). This is due to the higher latitude occurrence of warm ocean temperature and the minimum of summer baroclinicity which occurs in the N.H. as compared to the S.H.

About two-thirds of all cyclones occur in the N.H. Similarly, about two-thirds of all tropical cyclones form in the eastern as opposed to the western hemisphere.

As previously discussed (Gray, 1968), about 80-85% of tropical cyclones originate in or just on the poleward side of the inter-tropical convergence zone (ITCZ) or monsoon trough. Most of the remainder (~15%)

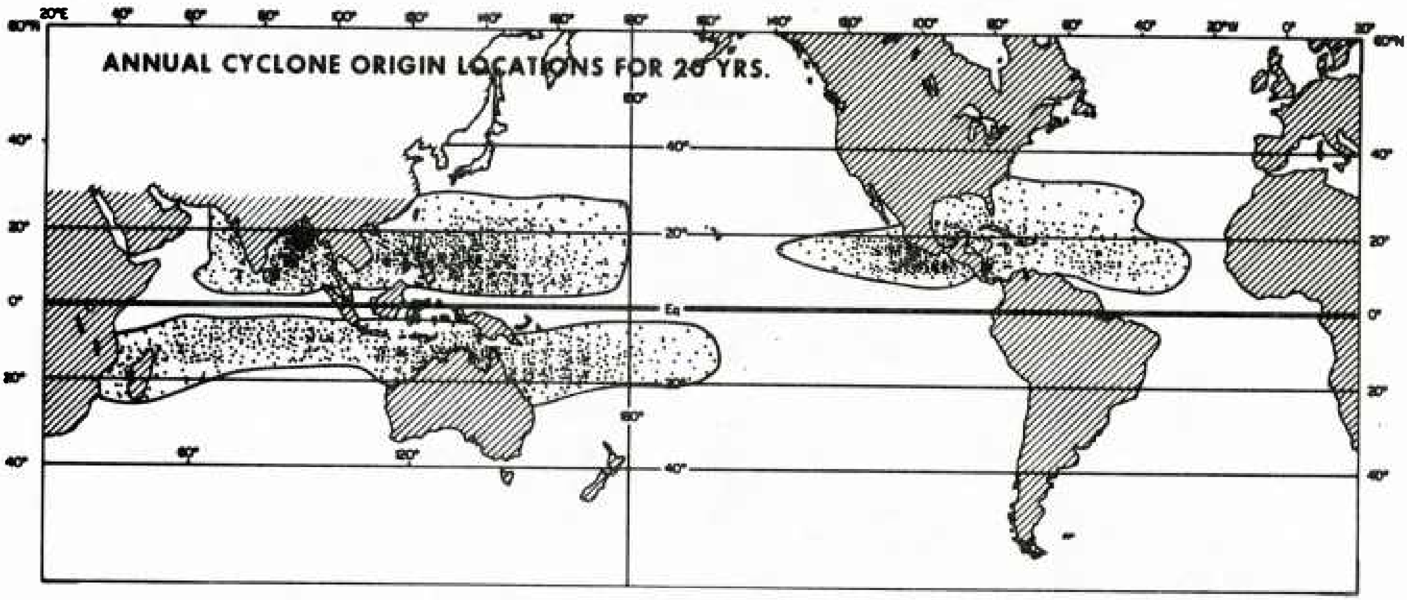

Fig. 2.1.

form in the trade winds (embedded systems as some people call them) at a considerable distance from the ITCZ but often in association with a special upper tropospheric flow pattern such as the TUTT (Sadler, 1978). The majority of Atlantic formations are not directly associated with a monsoon trough but are embedded formations within the trade winds.

There is another smaller class of subtropical or semi-tropical cyclones. They comprise about 3-5% of the global total of tropical cyclones. They form in subtropical latitudes in or near the baroclinic regions of stagnant frontal zones or to the east of upper level troughs. Subtropical cyclones are typically less intense than their purely tropical cousins, but often cover a larger area. This type of mixed tropical-baroclinic cyclone can cause many problems to the forecaster, however. They need more study. Subtropical formations are most prevalent in the northwest Atlantic and the northwest Pacific where warm core development can occur at a higher latitude than in the Southern Hemisphere or the northeast Pacific.

TABLE 2.1

Last 20-year Statistics on Tropical Cyclone Activity in the

Northern and Southern Hemisphere

N. Hemp.	S. Hemp.	N. Hemp.	S. Hemp.	TOTAL	% Deviation from 27 yr. Average	Ratio of N to S Hemp. Cyclones
1958	1958-59	52	29	81	-4	1.8
1959	1959-60	48	21	69	-14	2.3
1960	1960-61	48	22	70	-12	2.2
1961	1961-62	58	23	81	+2	2.5
1962	1962-63	50	28	78	0	1.8
1963	1963-64	49	23	72	-10	2.1
1964	1964-65	65	19	84	+5	3.4
1965	1965-66	56	23	79	-2	2.4
1966	1966-67	64	16	80	-2	4.0
1967	1967-68	63	28	91	+14	2.2
1968	1968-69	61	23	84	+5	2.6
1969	1969-70	49	23	72	-10	2.1
1970	1970-71	56	26	82	+3	2.1
1971	1971-72	70	27	97	+22	2.6
1972	1972-73	52	35	87	+14	1.5
1973	1973-74	46	28	74	-7	1.6
1974	1974-75	55	19	74	-6	2.9
1975	1975-76	47	29	76	-5	1.6
1976	1976-77	55	30	85	+7	1.8
1977	1977-78	47	20	67	-16	2.3
1978	1978-79	62	25	87	+2	2.5
1979	1979-80	48	28	76	-5	1.7
1980	1980-81	51	29	80	0	1.8
1981	1981-82	57	26	83	+4	2.2
1982	1982-83	55	24	79	-1	2.3
1983	1983-84	51	28	79	-1	1.8
1984	1984-85	61	35	96	+20	1.7
Total		1476	687	2163		
Average		54.7	25.4	80.1	± 7%	2.2
Maximum		70	35	97	+22	4.0
Minimum		46	16	67	-16	1.5
Range		24	19	30	38	2.5
Range/Seasonal Mean		.44	.74	.37	--	1.14

b. Seasonal Cyclone Basin Variability

In general the cyclone basins having the most cyclones have the least season to season variability on a percentage basis. Table 2.2 shows individual cyclone basin seasonal variability in percent. Variability is defined in percent as the ratio of the mean seasonal deviation ($\bar{D}$) without respect to sign to the long term seasonal average ($\bar{S}$) or $\frac{\bar{D}}{\bar{S}}$ x 100. ($\bar{D} = \frac{\Sigma |D'|_i}{n}$ where $|D'|$ is the deviation in the number of systems in any season from the long-term seasonal average for that basin and n the number of seasons). Note that the North Atlantic has the highest seasonal variability in tropical storm and hurricane frequency. By contrast, the NW Pacific has only slightly more than half as much season to season named storm variability. By this definition the Northern and Southern Hemispheres have a yearly variability of 10 and 14 percent respectively. The year to year global variability is but 9 percent by this definition.

TABLE 2.2

Mean Seasonal or Yearly Variation of Individual Basin Storm Frequency from the Long-term Basin Mean

1.	Northwest Atlantic	29%
2.	South Indian Ocean	27%
3.	Northeast Pacific	23%
4.	North Indian Ocean	22%
5.	Australia-South Pacific	20%
6.	Northwest Pacific	16%
Northern Hemisphere		10%
Southern Hemisphere		14%
Global Average (from Table 1)		9%

c. Seasonal Relationships Between the Different Basins

Are there correlations between active and inactive cyclone seasons of one storm basin with the activity of another basin? Is there any relationship between the N.H. seasonal cyclone activity and cyclone activity of the S.H. the season before or after?

There is a degree of annual compensation between basins. The ratio of yearly Northern to Southern Hemisphere cyclone frequency averages 2.2 but can vary from 1.5 to 4.0. Individual monthly variations are often large. Individual ocean basins can have wide year to year differences in cyclone occurrences as indicated in Table 2.3.

The statistical evidence of these data suggests that there are no meaningful relationships between the individual storm basins or between the Northern or Southern Hemispheres. For instance, it has been assumed by some that seasonal cyclone activity of the NW Atlantic and NE Pacific was oppositely correlated. The data of Table 2.3 do not support this. There also appears to be no significant relationship between cyclone activity in the NW Pacific and the North Indian Ocean, or between cyclone activity in the South Indian Ocean and the Australia-South Pacific region.

There does, however, appear to be a slight opposite relationship between the NE and NW Pacific regions. In the 11 seasons when the NE Pacific had 2 or more named storms above average, the NW Pacific averaged 24.6 cyclones vs. 27.6 cyclones for the 9 seasons when NE Pacific activity was 2 or more named storms below average. This is at best a quite weak relationship. There is no obvious appearing relationship between N.H. named storm activity with S.H. activity either in the season before or after.

TABLE 2.3

Yearly Variation of Tropical Cyclones by Ocean Basin

Year	S. Hemp.	NW ATL	NE PAC	NW PAC	N INDIAN	S INDIAN	AUS-S PAC	TOTAL
1958	1958-59	12	13	22	5	11	18	81
1959	1959-60	11	13	18	6	6	15	69
1960	1960-61	6	10	28	4	6	16	70
1961	1961-62	11	12	29	6	12	11	81
1962	1962-63	6	9	30	5	8	20	78
1963	1963-64	9	9	25	6	9	14	72
1964	1964-65	13	6	39	7	6	13	84
1965	1965-66	5	11	34	6	12	11	79
1966	1966-67	11	13	31	9	5	11	80
1967	1967-68	8	14	35	6	11	17	91
1968	1968-69	7	20	27	7	8	15	84
1969	1969-70	14	10	19	6	10	13	72
1970	1970-71	8	18	23	7	11	15	82
1971	1971-72	14	16	34	6	7	20	97
1972	1972-73	4	14	28	6	13	22	87
1973	1973-74	7	12	21	6	4	24	74
1974	1974-75	8	17	23	7	6	13	74
1975	1975-76	8	16	17	6	8	21	76
1976	1976-77	8	18	24	5	9	21	85
1977	1977-78	6	17	19	5	6	14	67
1978	1978-79	12	18	28	4	13	12	87
1979	1979-80	8	10	23	7	11	17	76
1980	1980-81	11	14	24	2	11	18	80
1981	1981-82	11	15	28	3	12	14	83
1982	1982-83	5	19	26	5	5	19	79
1983	1983-84	4	21	23	3	11	17	79
1984	1984-85	12	18	27	4	12	23	96
Total		239	383	705	149	243	444	2163
Average		8.9	14.2	26.1	5.5	9.0	16.4	80.1
% of Global Total		11	18	33	7	11	20	100
Maximum		14	21	35	9	13	24	97
Minimum		4	6	17	2	5	11	67
Range		10	15	18	7	8	13	30
Range/Seasonal Mean		1.12	1.26	.69	1.0	.89	.79	.35

It appears that there is thus no strong seasonal statistical relationship between the named storm activity of one storm basin with that of another basin nor of activity between the two hemispheres. This is not to say that there are not shorter 1-3 week period relationships between such cyclone activity. This has yet to be fully explored, however.

d. Clustering of Cyclones in Time

Tropical cyclones tend to cluster in time. One can observe 10-20 cyclones about the globe within an active 2-3 week period. These active periods are typically separated by 2-3 week periods when there is little cyclone activity. This cyclone clustering in time for the Northern and Southern Hemisphere for a 20-year period is portrayed in Figs. 2.2 and 2.3. Active periods typically produce 2-5 times the number of cyclones that would otherwise be expected from climatology.

Similar time clustering of weaker tropical weather systems such as cloud clusters is much less evident. Cloud cluster systems exist at nearly any time and can occur in large-scale environmental situations not conducive to cyclone genesis. It appears that active cyclone periods are a product of favorable large-scale general circulation changes in the tropical atmosphere which occur on time scales of about 15 to 25 days or so. Unfavorable genesis situations exist for similar and sometimes longer periods.

Figure 2.4 portrays global information (as opposed to the hemispheric data of Figs. 2.2 and 2.3) for the last 7 years on active and inactive periods of the formation of named tropical cyclones. The number of named storms whose initial detection date fell within the various shaded (active) and unshaded (inactive) periods is shown by

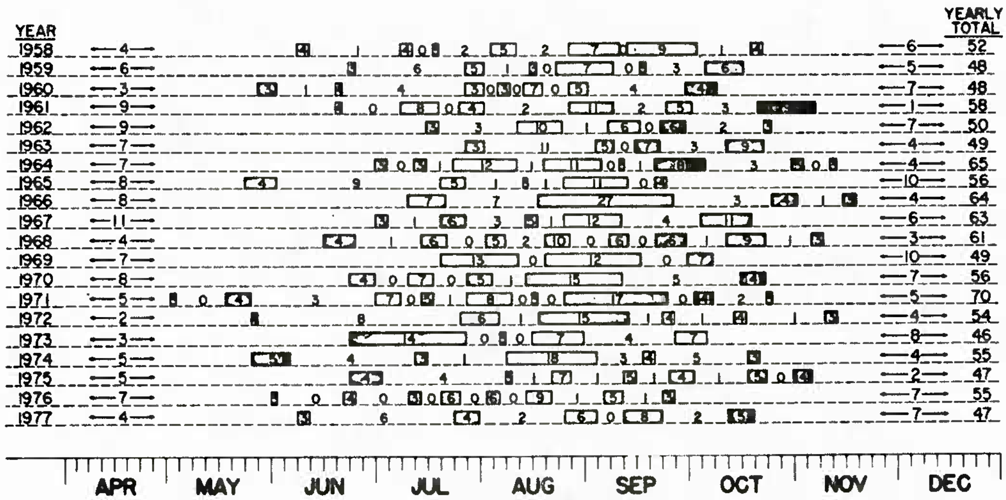

Fig. 2.2. Time and space clustering of Northern Hemisphere cyclone genesis. Numbers in shaded areas give the numbers of tropical cyclone formations during active genesis periods. Numbers of formations during inactive periods are also shown in areas without shading. Numbers between arrows indicate the numbers of cyclone formations before and after the active genesis periods (Gray, 1979).

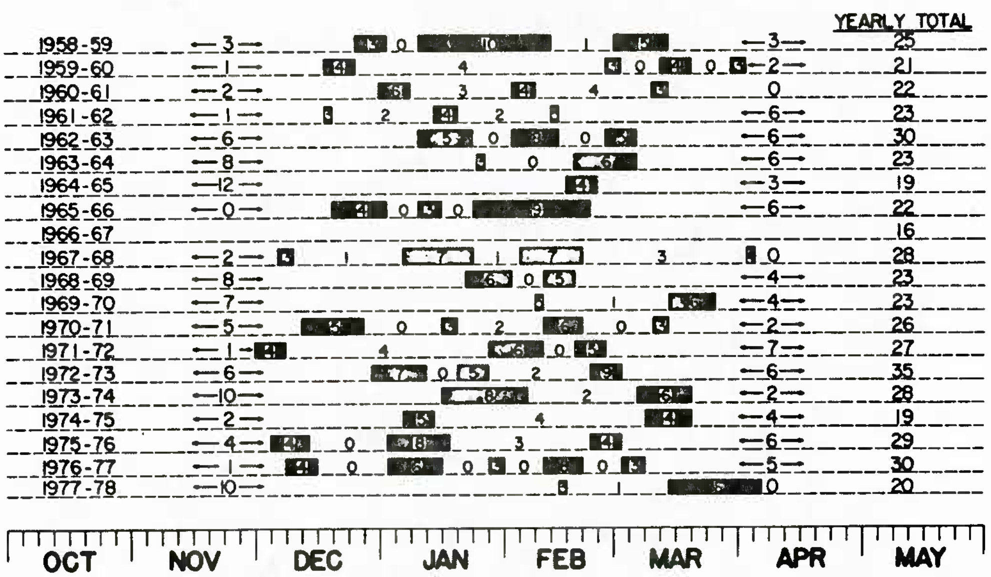

Fig. 2.3. As Fig. 2.2 except for the Southern Hemisphere (Gray, 1979).

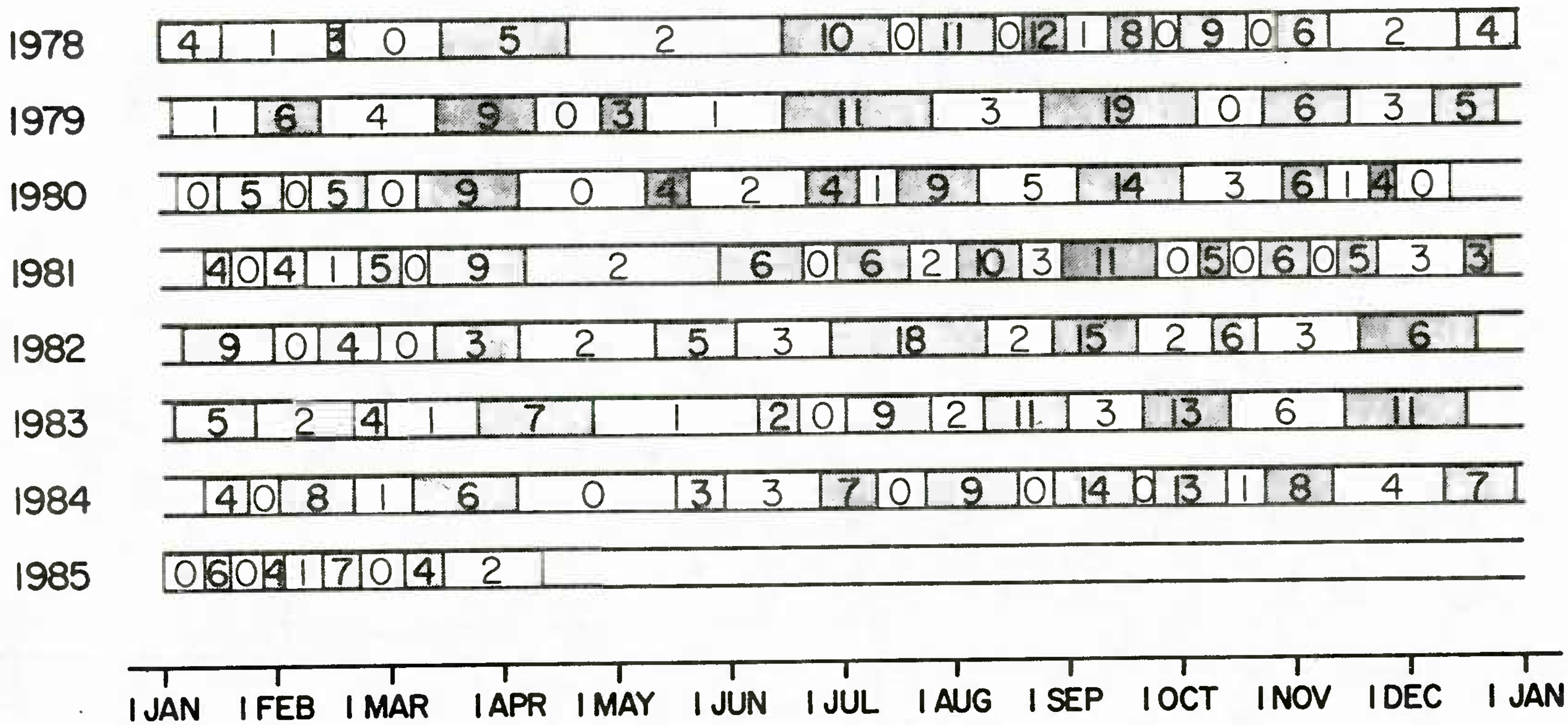

Fig. 2.4. Year and day portrayal of the clustering in time of the initial dates of the formation of all global named tropical cyclones. Shaded intervals indicate active periods, unshaded intervals inactive periods since 1978. Numbers of formations are indicated by the figure in the center of each active or inactive period.

the number within each time period. Even though the months of April to June have a concentration of inactive periods and the months of July to October a concentration of active periods, the back and forth oscillation of these 2-3 week periods of active and inactive storm intervals is evident in all years. Note how typical 15-25 day active periods of named storm formation alternate with 15-25 day periods of general inactivity. Although quite variable in length, active and inactive periods each average roughly 20 days or so in duration. On the average, about 7-8 named storms form during the typical active period while only 1 to 1 1/2 cyclones form during the usual inactive periods. This results in about 85% of the globe's named storms being formed during active periods as compared with only about 15% forming during a like number of days during inactive periods.

Global Tropical Cyclone Variability by Month. Table 2.4 gives a breakdown in number, deviation, percent, etc. of mean monthly frequency of global named storm formations for the average active and the average inactive period in each month. The annual average number of named storm formations per month is 6.7. April through June average 3.7 named storm formations per month while the period July through October shows an average of 10 formations per month or 2.7 times as many systems as occur during April through June.

It is interesting to speculate that the low storm activity during April through June occurs when convective lapse-rates over the N.H. land areas are at a maximum and smaller scale less organized convection can more easily break out and act to balance the troposphere's net radiational cooling. During August through October convective lapse-rates over land are more stable and conditions less conductive to

TABLE 2.4

Breakdown of average global named tropical cyclone formations by months - 1958-1985 and the rate of formations per month during active and inactive formation periods.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Monthly Ave.	Annual Total
Ave. No. per Month	6.7	6.2	5.1	3.1	3.4	4.6	8.7	11.0	11.7	8.4	5.8	5.4	6.67	80.1
Ave. % of Annual Total	8.4	7.7	6.4	3.9	4.2	5.7	11.0	13.7	14.6	10.5	7.2	6.7	8.33	100
Deviation from Annual Monthly Ave. of 6.7	0	-0.5	-1.6	-3.5	-3.2	-2.0	+2.0	+4.3	+5.0	+1.7	-0.9	-1.3	0	0
% Deviation from Annual Monthly Ave.	101	92	77	47	50	68	132	164	175	126	86	80	100	100
Ave. No. rate per Month Active Periods (Half of days)	11.3	10.5	8.7	5.4	5.8	7.8	14.8	18.7	19.9	14.3	9.9	9.2	11.4	136
Ave. No. rate per Month Inactive Periods (Half of days)	2.0	1.9	1.5	0.9	1.0	1.4	2.6	3.3	3.5	2.5	1.7	1.6	2.0	24

smaller scale and less organized deep convection. To bring about the needed amount of rainfall to accomplish hemispheric energy balance requirements, it is necessary that convection occur more over the oceans and be more organized in weather systems, like the tropical cyclone.

Active and inactive periods occur about 50 percent of the time. During average active conditions between July and October one can expect tropical cyclones to form about the globe at a rate of about 17 named storms per month (or about 1 storm every 2 days) vs. only 3 named storms per month (or 1 per 8 days) in the inactive periods of these same months. During the lower frequency months of April through June the average active period experiences formation at a rate of about 6 named storms per month (or 2 per 10 days) vs. only a little more than 1 named storm per month (or 1/3 storm per 10 days) during the inactive periods of these slack months.

Named Storm Frequency Deviation from Expected Cyclone Frequency for that Date. Another way to portray this information is to show these active and inactive periods as a percentage above or below what would be expected for each period based on the 27-year climatology. Figure 2.5 is similar to Fig. 2.4 but information is expressed as a percent of what would have been expected on that date from climatology. When no named storms occurred during an inactive period a zero is given with a bracketed figure indicating the number of expected named storms which should have occurred during this period based on climatology. This figure gives a more realistically relative portrayal of the active and inactive periods during the July through October period than Fig. 2.4 is able to do. It also better portrays the active vs. inactive periods during the April through June period of slack storm activity.

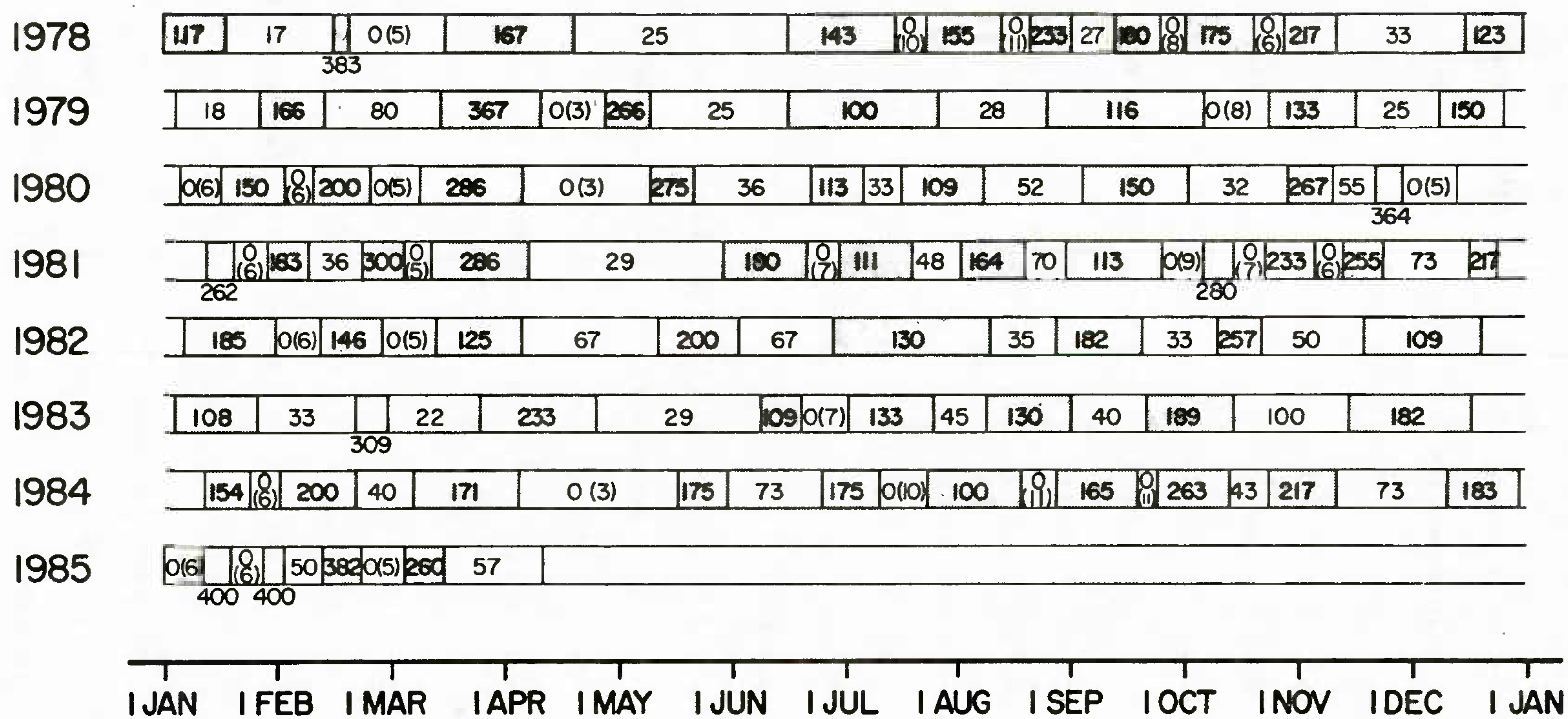

Fig. 2.5. Similar to Fig. 2.4 except that active (shaded) and inactive (unshaded) formation periods are expressed as a percentage of the named storm activity which would be expected for that date based on climatology. When no named storms occurred during an inactive period a zero is given with a bracketed figure indicating the number of expected named storms which would have been anticipated from climatology.

e. Possible Relationships of Active-Inactive Periods with the 40-50 Day Oscillation.

The average period between successive active periods or between successive inactive periods is on the average about 40 days or so. These oscillation periods of named storm activity appear at times to have a correspondence with the 40-50 day oscillation which has recently been detected in tropical surface pressure, upper-level winds, and Outgoing Longwave Radiation (OLR).

This 40-50 day tropical oscillation first detected by Madden and Julian (1971, 1972) has been hypothesized by Anderson (1984) to be a consequence of a 40-50 day modulation of convection within the Hadley cell circulation. Anderson reasoned that this oscillation is a consequence of the period of travel time of individual air particles through the Hadley cell. A 40-50 day oscillation appears often to be associated with a low latitude 40-50 day variation in 200 mb minus 850 mb zonal wind. Such wind shears are known to be associated with the modulation of tropical cyclone frequency in the monsoon trough regions.

A precursory inspection of the active and inactive periods of Fig. 2.2 by the author shows that they were often associated with differences in equatorial western North Pacific 200 mb minus 850 mb zonal wind shear. But this relationship did not always hold up. The author has previously noted (unpublished) a 60 to 40% or more modulation in northwestern Pacific typhoon activity associated with a 40-50 day oscillation of 200 mb minus 850 mb vertical wind shear as determined by the Truk (7°N, 152°E) sounding during a 10-year period of the 1970's. T. Murakami of the University of Hawaii (1985 - personal communication) also has indicated a northwestern Pacific typhoon relationship with a 40-50 day oscillation in outgoing longwave radiation.

There appear to be few subjects on the climatology of global tropical cyclones more in need of a thorough examination than this question of how well global active and inactive storm periods are associated with (or modulated by) such 40-50 day global oscillations in tropospheric wind, surface pressure, and OLR. This is a pressing topic for future research. Whether related or not, new research needs to be directed towards global general circulation conditions which bring about such changes in active and inactive storm periods. The author is of the opinion that as global numerical modeling advances in its sophistication, and as new empirical studies are undertaken, that such periods of global active and inactive storm activity may be able to be forecast with some degree of skill. This would likely require utilization of a very insightful combination of empirical knowledge and numerical modeling products.

f. Factors Leading to Inter-Annual Differences in Cyclone Frequency

It is very difficult to isolate the causes of variability of tropical cyclone frequency or track from season to season. One can, of course, say surface pressure was higher or lower than normal or that wind currents were stronger or weaker than normal, etc. It is observed that anomalous tropical cyclone activity is frequently inversely related to storm basin Sea Level Pressure (SLP) and/or directly related to sea surface temperature (SST). But these associations do not explain why the SLP, SST, or wind deviations vary from season to season.

It appears that some of the inter-annual variations in seasonal cyclone activity, particularly in the Atlantic and South Pacific, can be associated with the presence of El Nino events or by the magnitude of the Southern Oscillation (i.e. - Taihiti minus Darwin sea level pressure). Atlantic hurricane activity also has a surprising association with the east vs. west wind phase of the 30 mb Quasi-Biennial Oscillation (QBO) of equatorial stratospheric wind.

This section discusses the influences of the El Nino (EN), the QBO, and SLP on seasonal tropical cyclone frequency.

1) The El Nino

As discussed by the author (1984a), tropical cyclone activity in the Atlantic basin is noticeably suppressed during El Nino years. The Atlantic had less than half as many hurricane days per season (10.9) in the 16 years of strong or moderate El Nino events of this century as during the other 69 (non-El Nino) seasons (23.2 days). This appears to be a result of the anomalously strong 200 mb westerly winds which occur over the southern portions of the Caribbean basin during these years.

The large reduction in tropical cyclone activity during El Nino years is not experienced, however, in the other tropical cyclone ocean basins. Table 2.5 shows the number of hurricanes and tropical storms that occurred in the three other Northern Hemisphere tropical cyclone ocean basins relative to the occurrence of a moderate or strong El Nino year. Although storm numbers may be somewhat under-reported in earlier years (particularly the weaker storms), the relative magnitude of seasonal tropical cyclone activity before, during, and after a moderate or strong El Nino year should be generally reliable. Note that El Nino conditions do not appear to affect hurricane and tropical cyclone activity in the three other N.H. tropical cyclone basins. There is also

TABLE 2.5

Northern Hemisphere Mean Seasonal Number of Hurricanes and Tropical Storms for One Year Before (-1), During (0), and One Year After (+1) a Moderate or Strong El Nino.

Ocean basin	EN -1	EN 0	EN +1	Other years
North Indian Ocean (1911-82), 12 events	5.3	5.5	6.9	5.6
Northwest Pacific (1900-82), 15 events	25.8	26.6	26.8	25.7
Northeast Pacific (1949-82), 6 events	12.0	12.3	11.2	11.9
Total	43.1	44.4	44.9	41.2
Atlantic (1900-84), 16 events	7.8	5.4	8.6	9.0
Atlantic (1900-84) (Hurricane Days)	19.0	10.9	25.1	23.2

little modulation of cyclone frequency in the S.H. as a result of El Nino events.

The author does not mean to imply that the locations and tracks of tropical systems are not influenced by the El Nino in these other global storm basins, however. El Nino years are associated with a larger number of tropical cyclones in the NE Pacific basin which track further westward than normal. El Nino events also cause South Pacific storms to form much further eastward than normal. And, as discussed by J. Chan (1985), in the year following an El Nino year, the seasonal named storm activity in the NW Pacific Ocean frequently tends to commence at a later date in the season.

Tropical cyclone activity in the South Pacific during the 1982-1983 storm season especially emphasized these features. The strongest El Nino of this century was occurring during this period. Eight named storms formed east of 160°E in contrast to the previous 13-year average of 2.5. And, 6 named storms formed east of 160°W in this single season, equalling the number of such systems for the previous 13 years. In addition, 5 of the 1982-83 systems had recognizable cyclone tracks well east of 140°E, with 2 South Pacific systems moving as far east as the longitude of San Francisco.

Figure 2.6 portrays the 200 mb minus 850 mb shear of the zonal wind for the months of April 1982 and April 1983. Note how much further east the negative values extend in the El Nino period of April 1983 in comparison with the non-El Nino period of April 1982. Tropical cyclone formation is favored with such negative values, which imply increasing easterly flow with height equatorward of the cyclone formation latitudes.

This high level of eastern South Pacific cyclone activity during the 1982-83 season does not mean that the entire Australia - South Pacific had above average activity. Nicholls (1984) has recently reported that low values of the Southern Oscillation Index (SOI) cause a significant reduction in early season Australian region tropical cyclone activity. Activity in the South Indian Ocean and Australian region was below average during the 1982-83 hurricane season and overall, the Southern Hemisphere had an average amount of tropical cyclone activity.

2) The Quasi-Biennial Oscillation and Tropical Cyclone Activity

In the Atlantic during the period 1950-1985 there have been twice as many hurricane days during the seasons when the 30 mb equatorial stratospheric winds were from the west (~ 34 hurricane days per year on average) in comparison when 30 mb QBO winds were from the east (~16 hurricane days per year). A satisfying physical explanation has yet to be

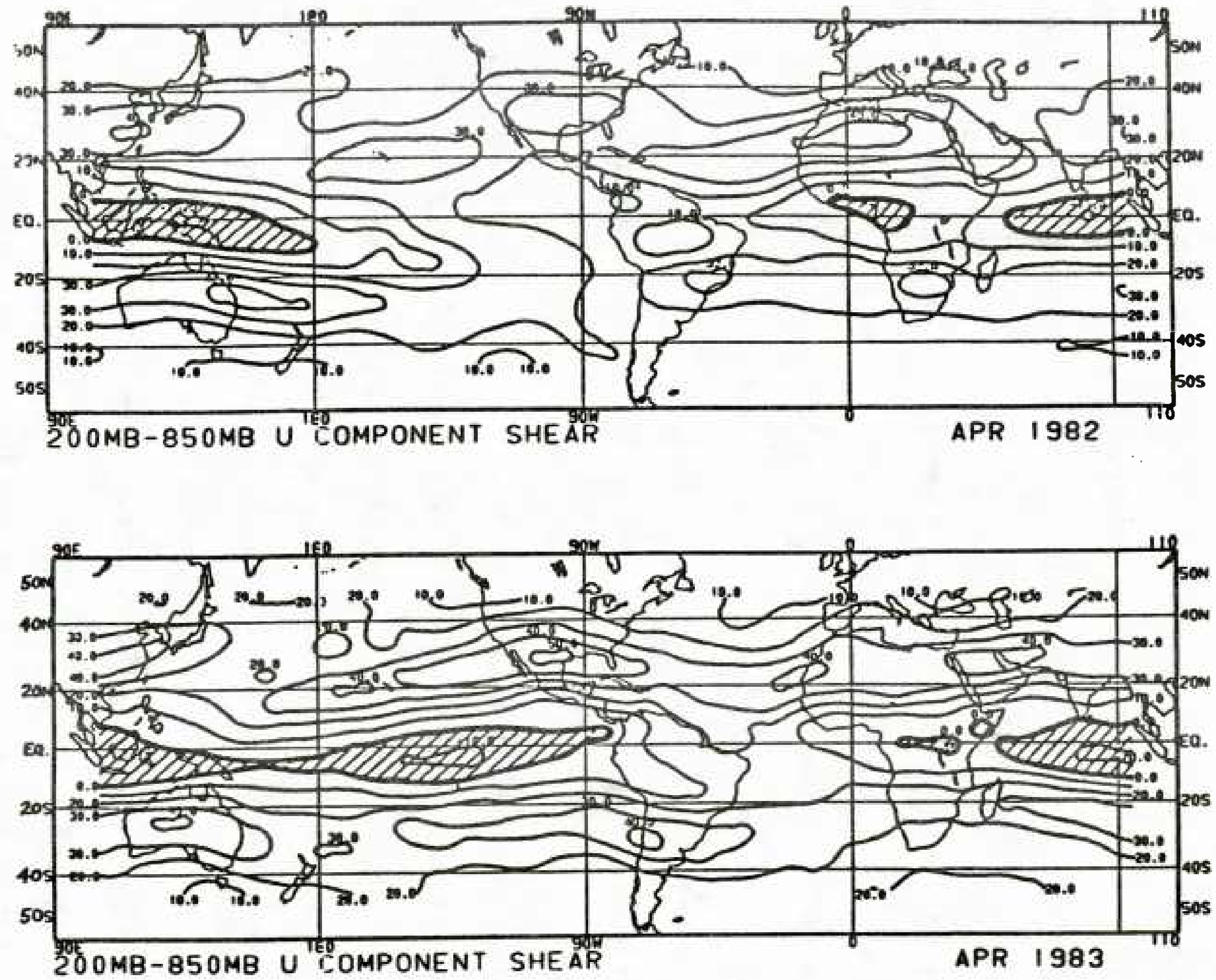

Fig. 2.6. Observed mean zonal vertical wind shear between 200 mb and 850 mb for April 1982 (upper) and April 1983 (lower). Negative values, indicated by diagonal hatching, correspond to 200 mb zonal winds that are weaker from the west, or stronger from from the east, than the zonal winds at 850 mb. Units are meters per second. (Personal communication to the author from C. O. Erickson, 1983).

advanced for this relationship, particularly since it has not been detected or is very weak in the other tropical cyclone basins.

3) Surface Pressure

It is well known that tropical cyclone formation is dependent upon surface pressure. Cyclone formation is more likely when monthly and seasonal surface pressure is systematically below average. There are also associations between surface pressure prior to the onset of the tropical cyclone season and seasonal cyclone activity.

Nicholls (1984) has presented strong statistical evidence for the correlation of early season Australian region tropical cyclone activity with the Darwin (12.5^{o}S) sea level pressure. When Darwin pressures are higher than normal in the winter period of July through September, then October to January tropical cyclone activity in the Australia region is suppressed. Activity is enhanced when winter surface pressure is lower than normal. Shapiro (1982a, 1982b) also has related surface pressure in the period of May through July to August through October Atlantic hurricane activity. The author also has verified such relationships for the Atlantic and developed an Atlantic seasonal forecast scheme based on these associations of the El Nino, QBO, and sea level pressure (Gray, 1984b).

g. Track Characteristics

Figure 2.7 shows the track of tropical cyclones for a 3-year period. A large variability in track is evident. However, this figure cannot show well many of the systematic track differences between the different storm basins. For instance:

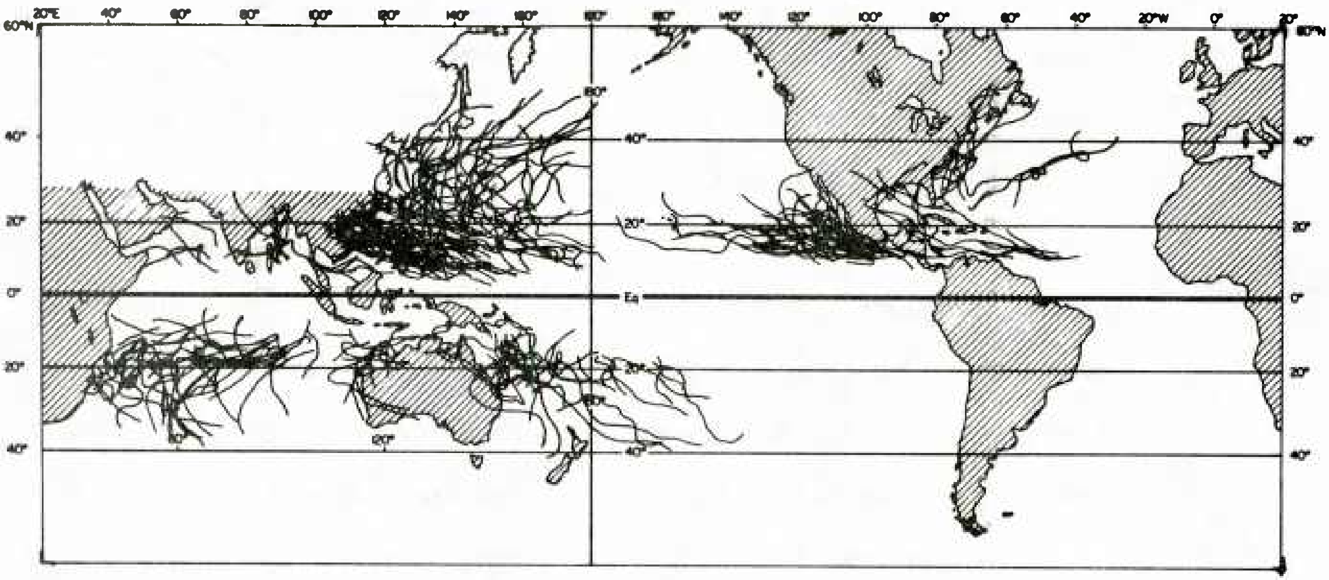

Fig. 2.7. The tracks of tropical cyclones for a 3-year period.

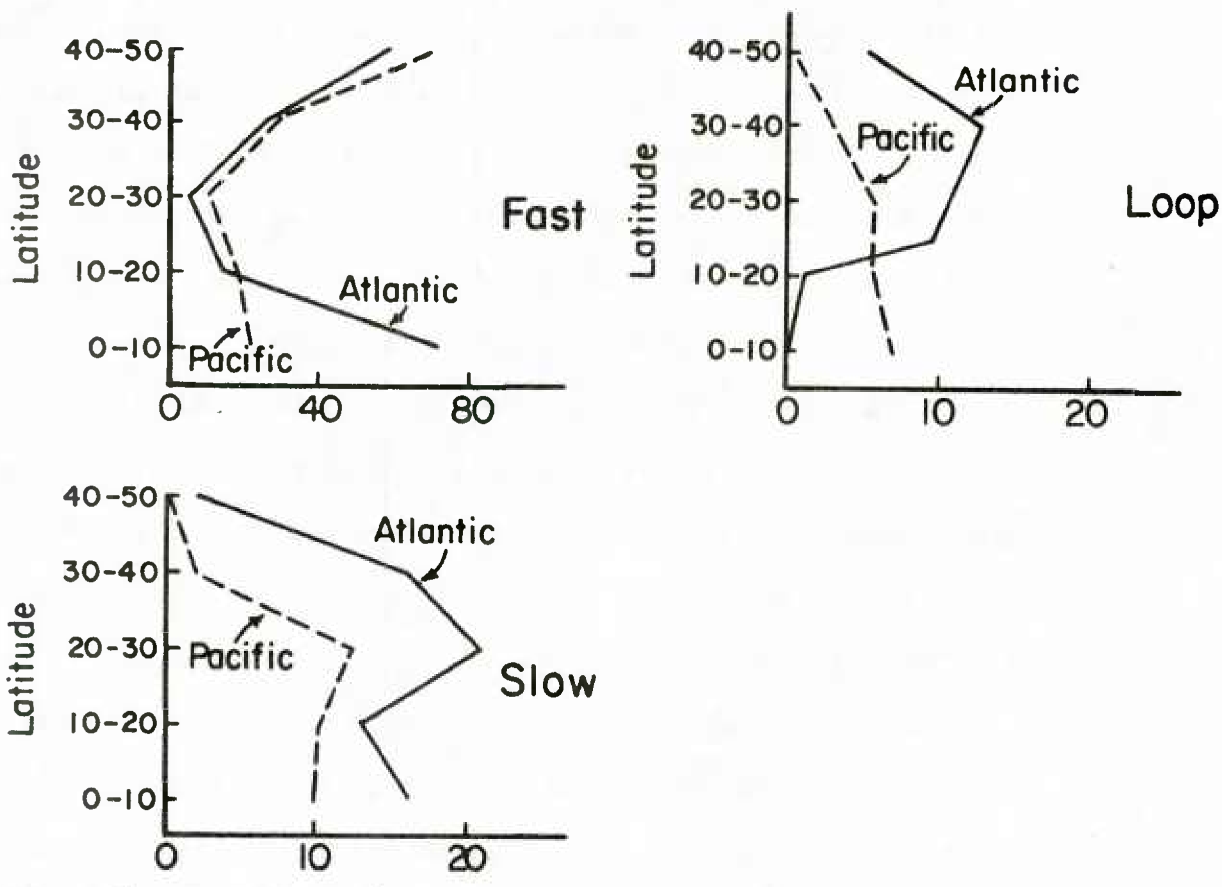

Fig. 2.8. Percentage of storms in the Atlantic and western North Pacific which are fast (> 7.5 m/s), slow (< 2.5 m/s) or looping vs. latitude. (From Xu and Gray, 1982.)

1. The latitudinal distribution of fast (> 7.5 m/s), slow (< 2.5 m/s), and looping motion tropical cyclones are different in the Atlantic than the NW Pacific. Figure 2.8 shows that:

a) there is a much higher percentage of fast moving tropical cyclones at low latitudes in the Atlantic in comparison with the Pacific.

b) the percentage of slow moving cyclones in the Atlantic is nearly twice as much as in the NW Pacific.

c) the percent of low vs. high latitude cyclones which loop is very different in the two basins. The Atlantic has substantially more looping cyclones at high latitudes than the NW Pacific and the NW Pacific has more looping at low latitudes.

2. The percentage of slow moving, erratic or stationary tropical cyclones in the Australian region is the highest in the world. This is why track forecasting in the Australian region is the most difficult in the world.

3. The South Pacific has tropical cyclones whose entire lifecycle occurs while they are moving in an easterly direction. This is uncommon in the other basins.

4. Because of restrictions of land or cold water to their poleward sides only a very small number of named tropical cyclones in the North Indian Ocean and the NE Pacific experience recurvature. This reduces the often difficult forecast problems associated with recurvature and acceleration which occur when cyclones enter a westerly steering environment. It is not surprising that these regions are judged to have the least forecast track difficulty. Forecast difficulty, in general, goes up with latitude.

Neumann and Pelissier (1981a, 1981b) define forecast skill as the degree to which it is possible to improve on a CLImatology-PERsistence (or CLIPPER) forecast track. The degree to which a cyclone track deviates from the track specified by climatology-persistence is a measure of the degree of forecast difficulty. Using this criteria, Pike (1985) has classified the 6 different global basins by their track forecast difficulty at 24, 48, and 72 hours (see Table 2.6). This table shows that the most difficult basin to forecast is that of the

TABLE 2.6

Average Forecast Difficulty (FDL) in n mi, and normalized FDL (NFDL), ranked by basin from most to least difficult (from Pike, 1985).

Rank and Basin	24 hr FDL	24 hr NFDL	48 hr FDL	48 hr NFDL	72 hr FDL	72 hr NFDL
1 S.W. Pac.-Aust.	130	1.37	272	1.34	393	1.32
2 North Atlantic	113	1.19	250	1.24	367	1.24
3 Western N. Pac.	99	1.04	225	1.11	341	1.15
4 S.W. Indian	87	0.91	183	0.91	270	0.91
5 Eastern N. Pac.	78	0.82	159	0.79	233	0.78
6 North Indian	63	0.67	124	0.61	177	0.60
Mean of all basins	95	1.00	202	1.00	297	1.00

South-Pacific/Australia region. Forecasts in this region are more than twice as difficult at 72 hours as forecasts of the North Indian Ocean and nearly twice as difficult as those of the NE Pacific. The Atlantic is only slightly less difficult than the South Pacific/Australia region. The NW Pacific is the third most difficult basin for track forecasting.

This concept of forecast difficulty appears to be very useful in determining realistic forecast skill differences between the different basins and even different individual cyclones. It is suggested that track forecast skill in all ocean basins be discussed in terms of how well track forecasts can improve on climatology-persistence.

Discussion. It is important that TC forecasters have an understanding of the important regional differences in tropical cyclone behavior. The background climatology in the various storm basins exhibits important differences. One must exercise care in applying forecast rules or in interpreting research results written about the tropical cyclones of one storm basin to another basin. In particular, those aspects related to a cyclone and its environment interaction can be different in the various basins. For instance, the US tropical cyclone literature, in its concentration on Atlantic cyclones, has tended to emphasize easterly waves. However, the easterly wave concept is much more applicable to the monsoon trough-free Atlantic than to the other monsoon dominated storm basins. Cross hemispheric influences are also generally less important in the Atlantic than in some of the other basins.

A single all encompassing and simple model of tropical cyclone and environmental interaction which is applicable in all of the global storm basins will likely not be forthcoming. Although the inner circulation features of the tropical cyclone are similar in all of the storm basins, the surrounding cyclone environmental linkages to the cyclone's inner circulation can be noticeably different in the various storm basins.

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3. Tropical Cyclone Formation

a. Background Discussion

It is often difficult to assess the Tropical Cyclone (TC) development or non-development potential of a tropical disturbance (i.e. - cloud cluster or easterly wave) from the usual available satellite images and synoptic map analyses. This is because the formation potential of a tropical disturbance does not relate well to the amount of meso-scale deep convection occurring within it. Also the synoptic-scale surrounding disturbance wind field differences which are associated with formation vs. non-formation are often difficult to objectively evaluate from normal weather map analyses. Many TC formations occur within synoptic-scale flow patterns of little or no obvious difference from synoptic-scale flow patterns of systems which do not develop. There is also the problem of not knowing what specific distinguishing characteristics to look for in the weather maps or in the satellite pictures. It is frequently observed that large and heavily raining disturbance systems do not develop into named storms while other cloud cluster disturbances with less deep convection do.

Low level aircraft reconnaissance investigative flights from Guam - which go out to reconnoiter the formation potential of tropical disturbances that may develop into named storms - attest to this difficulty. These are expensive flights. They would not be made if a better assessment of the development potential of a tropical disturbance were possible through a combination of synoptic map analysis and satellite pictures.

b. Tangential Wind Differences

Our project's TC rawinsonde compositing research - which has been directed to this question over the last decade (Zehr, 1976; Erickson, 1977; McBride, 1979; Lee, 1986a, 1986b) - has shown that one of the primary factors distinguishing between the average developing and the average non-developing tropical disturbance is (given satisfactory climatological conditions) the magnitude of the disturbance's surrounding (3-6^{o} radius) low and middle level environmental wind fields. Low and middle tropospheric tangential wind patterns around the average developing disturbance are, on average, two to three times greater than for the average non-developing disturbance. These earlier measurements are being better validated with more data and more stratified and refined compositing technology by Lee (1986a). Figures 3.1 and 3.2 show vertical cross sections of Lee's new rawinsonde composites of the radial distribution of tangential winds for the average developing and the average non-developing prominent cloud cluster systems in the western North Pacific. This includes over 10 years of rawinsonde information from many hundreds of cases. Note that developing cloud cluster systems have stronger surrounding tangential wind fields. Unfortunately, at the early stages of formation these differences of 2-3 m/s in mean tangential wind at 4-6^{o} radius are often difficult to assess in the individual case.

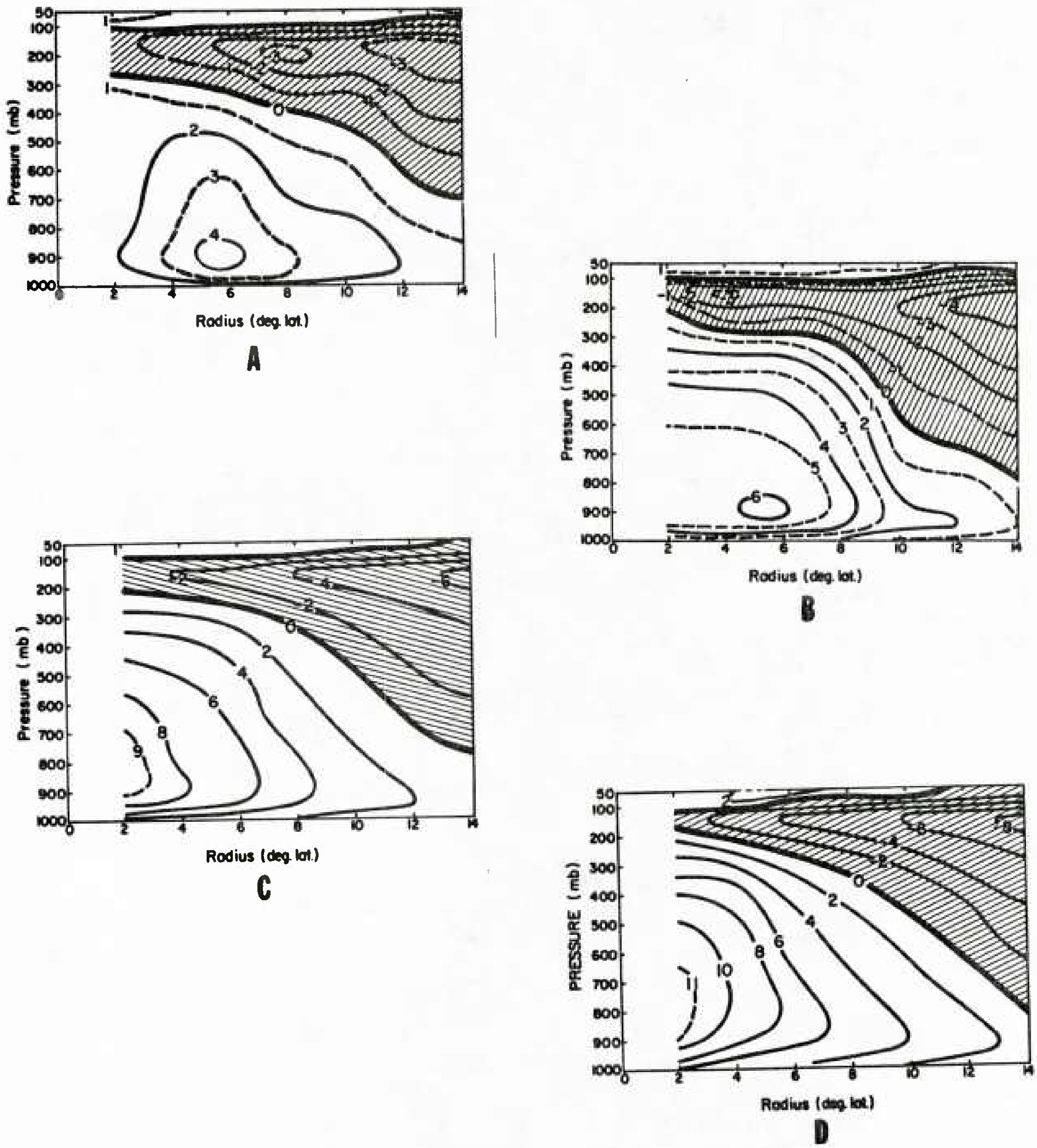

Fig. 3.1. Rawinsonde composite of mean tangential wind speed (in m/s) around a progressively intensifying developing tropical cloud cluster system in the western North Pacific two days before it became a named tropical storm (diagram A), one day before it became a named storm (diagram B), on the day it is named (diagram C), and one day after it was named a tropical storm (diagram D) - from Lee, 1986a.

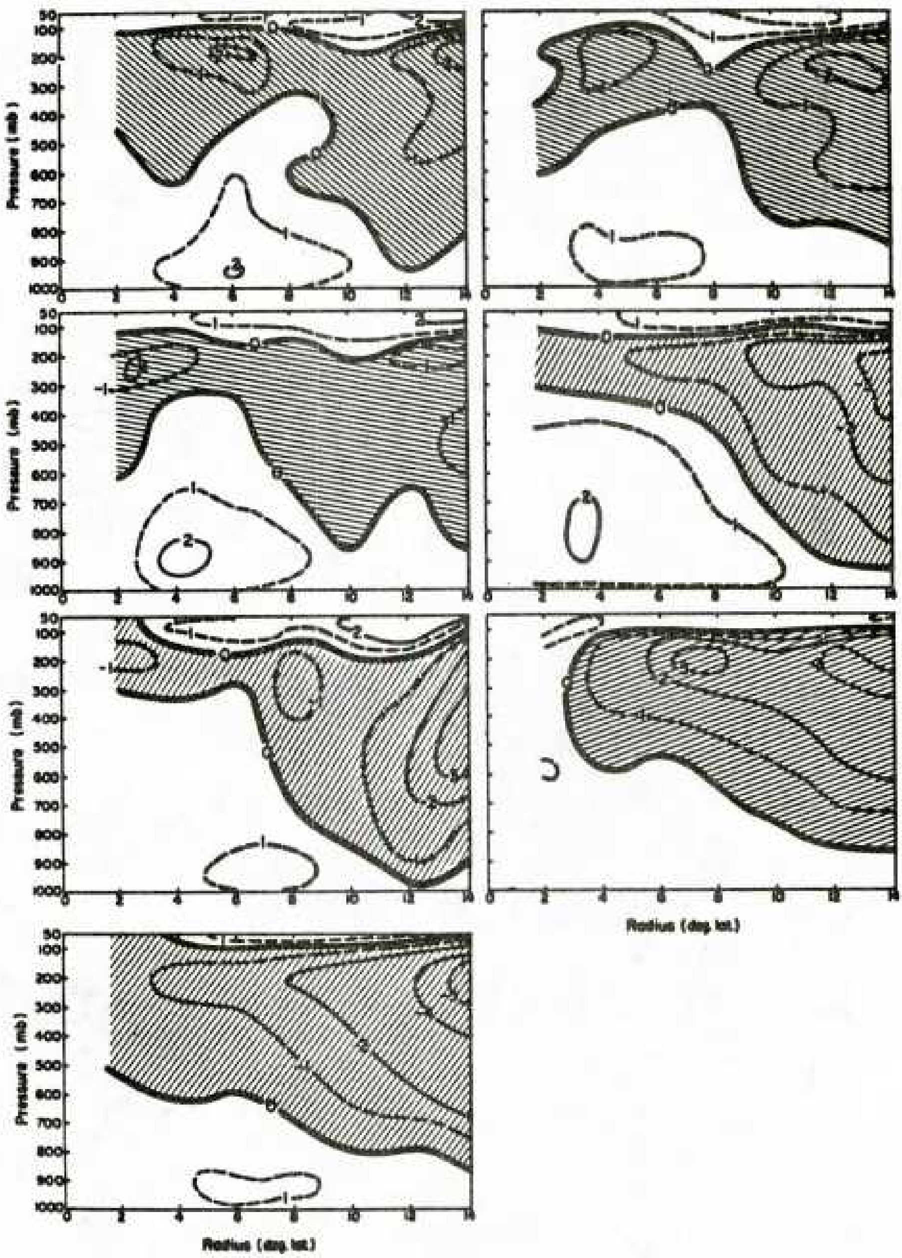

Fig. 3.2. Rawinsonde composite in the western North Pacific of tangential wind (in m/s) for three consecutive days (A, B, C) of a persistant non-developing tropical cloud cluster (column 1), of a non-persistent non-developing cloud cluster (column 2), with maximum cluster development on day B. The bottom figure on the left is the same information but for the average tangential wind relative to the same location points on the same day number and same location one year before and one year after each TC developing and non-developing. This bottom diagram has been termed the mean background environmental conditions (from Lee, 1986a).

c. Asymmetry of the Developing Disturbance's Tangential Wind Field

It is also observed that the low level tangential wind fields around the developing cloud cluster system are, in the initial stages of formation, frequently quite asymmetrical. Tangential wind fields become progressively more symmetrical as development proceeds. This is usually an evolutionary process. In the early formation stages strong winds are typically found only on one side of the disturbance. If development takes place, one observes that the tangential wind fields around the disturbance gradually become more symmetrical as it evolves into a stronger vortex. If this progressive transformation from strong winds on one side of the disturbance to a more symmetrical wind field does not occur within a 2-3 day period, named storm development typically will not occur.

In these early stages of the tropical cyclone formation process, the tangential wind spin-up by the system's symmetrical circulation of mean in-up-and-out radial-vertical circulation is insufficient to explain the observed increase of the disturbance's tangential winds. Early stage formation in most cases requires asymmetrical tangential wind increase.

These ideas are being verified by new research by Lee et al. (1986) and Lee (1986b). He is finding that a large fraction of the early stage tangential wind pickup of the newly developing pre-TC disturbance occurs as a result of selective side inward momentum convergence due to environmental forcing (or eddy processes) at large distances from the disturbance. These inward eddy momentum transports typically manifest themselves in selective packets of high wind speed air which are advected from the environment to one side of the disturbance. We refer to such asymmetrical inward momentum transports as external forcing.

For the 80 percent of global TC's which develop within a broad monsoon trough region, these synoptic-scale packets of wind surge most frequently occur on the equatorwards side of the disturbance. For TC development embedded in the trade winds, this type of wind surge more often occurs on the disturbance's poleward side.

It appears that these environmental driven selective azimuthal side inward momentum surges are frequently a primary factor in the early stage TC formation process. Disturbances which do not develop typically do not have such selective side momentum surges; or, if such surges occur without formation, the initial vorticity field of the non-forming disturbance was already too weak to start with.

Once the development process has been underway for 1-2 days, the asymmetric part of the tangential wind field weakens and winds become more symmetrical. The importance of the selective side environmental wind surge then diminishes. The disturbance's symmetrical radial and tangential circulations then become more efficient and become the major driving mechanism for further vortex growth.

These selective side disturbance wind increases more frequently occur on the disturbance's equatorward side. They often have their origin from opposite hemisphere wind surges from cold frontal penetration into the tropics as discussed by Love (1985a, 1985b) - Figs. 3.3 and 3.4 - or by Lee (1986b) and Lee et al. (1986). Sometimes these wind surges manifest themselves in long east-west oriented equatorially Cb cloud lines which curve around the disturbance's east side. These cloud lines are often a tell-tale indication of tangential eddy wind pick-up on the equatorial side of the potentially developing disturbance.

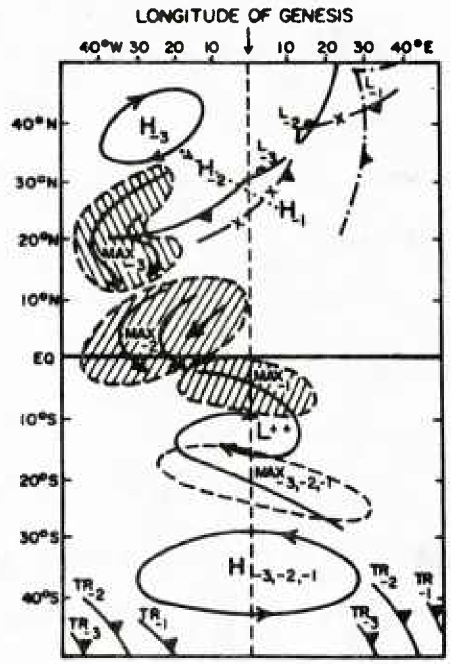

Fig. 3.3. Idealized gradient level streamline chart for three days preceding tropical cyclone genesis in the Southern Hemisphere. Subscripts -3, -2, -1 refer to the position of the synoptic feature that number of days before genesis. The momentum burst (isotach maximum) has been shaded (from Love, 1985b)

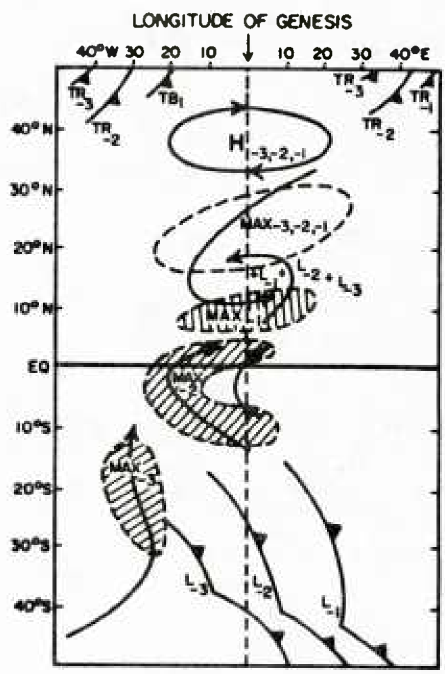

Fig. 3.4. Same as Fig. 3.3, but for the Northern Hemisphere.

Such special external forcing events typically last only a few days. They appear to initiate a lowering of the surface pressure near the disturbance's center through the adjustment of surface pressure to the wind field. This wind induced pressure decrease appears to be responsible for the early lowering of the distubance's central pressure. This contributes to the development of a following, more symmetrical, vortex circulation. If other necessary conditions for TC development - such as climatologically favorable conditions, relatively high initial disturbance vorticity, etc. - are present, then the surge will be the catalyst for the initiation of the development process. Development appears then to cross a critical stage from which growth can proceed to named storm stage. The disturbance initial stage mean vorticity field must be high enough, however, such that the selective side wind surge can reach this critical stage.

d. Example of Equatorial Wind Surge

Prior to the formation of Tropical Cyclone No. 18 in the Arabian Sea in 1979, satellite imagery and the European Center for Medium Range Weather Forecasting (ECMWF) map analysis show a series of frontal systems moving eastward in the South Indian Ocean (Figs. 3.5a, 3.5b, and 3.5c). A wind surge type flow similar to that described by Love (1985b) appears to propagate equatorward behind the shear lines associated with these fronts. This brings about a strengthening of the low-level wind maximum along the Somali Coast. This wind maximum then progresses eastward across the entire Arabian Sea. This initial cross-hemisphere surge increased the westerly winds on TC-18's southern side and

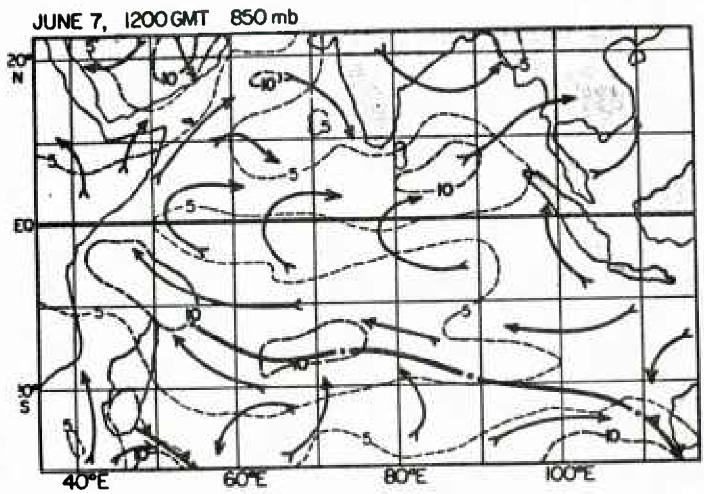

Fig. 3.5a. ECMWF analyzed 850 mb flow at 1200 GMT 7 June. Positions of the surface cold fronts and shear lines behind the cold fronts (long dash-dot) were interpreted by the authors from available satellite, pressure and wind data. Isotachs (dashed) are given in m/s (from Lee <u>et</u> <u>al</u>., 1986).

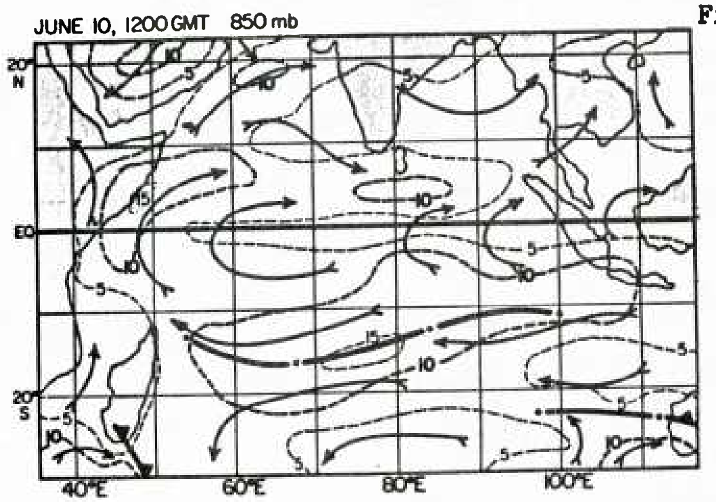

Fig. 3.5b. Same as Fig. 3.5a, but for 1200 GMT 10 June.

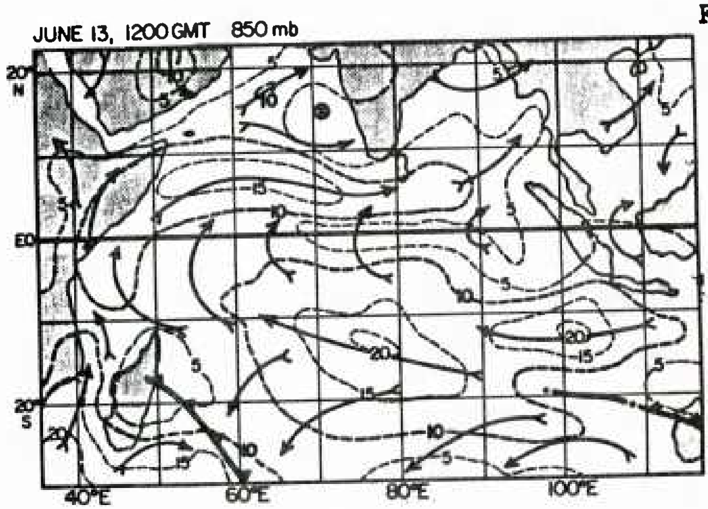

Fig. 3.5c. Same as Fig. 3.5a, but for 1200 GMT 13 June. Approximate location of the incipient tropical disturbance, TC 18-79, is indicated by X.

appeared to be the formation catalyst for its later development. This initiated the start of a progressive enhancement of the disturbance's low-level tangential circulation starting on 15 June (Fig. 3.6a)

Twenty-four hours later at 1200 GMT 16 June (Fig. 3.6b), the maximum wind to the disturbance's south changes very little; however, low-level cyclonic flow has now spread to the east and north sides of the developing system. Note how the 2 m/s cyclonic isotach has completely closed around the center. By 1200 GMT 17 June (Fig. 3.6c), the maximum wind area has increased to 23 m/s and moved closer to the system center. The cyclonic wind region now has virtually spread over almost the entire area. This gradual transformation of cyclonic shear to cyclonic curvature is similar to that of many other cases.

At higher latitudes we often see similar types of wind surges originating within the trade winds on a disturbance's poleward side. In a similar fashion to the equatorial surge of the above case, the tradewind surge will also progressively spread around the disturbance and cause a general enhancement of the symmetrical circulation.

e. Asymmetric Flow in Composited Wind Fields

These selective side asymmetrical wind surges are even present in the rawinsonde composite data sets which, due to the averaging of many cases, would tend to smooth out much of the wind asymmetries which are present in individual cases. Figure 3.7 shows one-day progressive differences in the build up of tangential winds around rawinsonde composite averages of many developing disturbances in the western North Pacific. A comparison with a similar one-time rawinsonde composite of prominent tropical disturbances (right diagram) which do not develop is

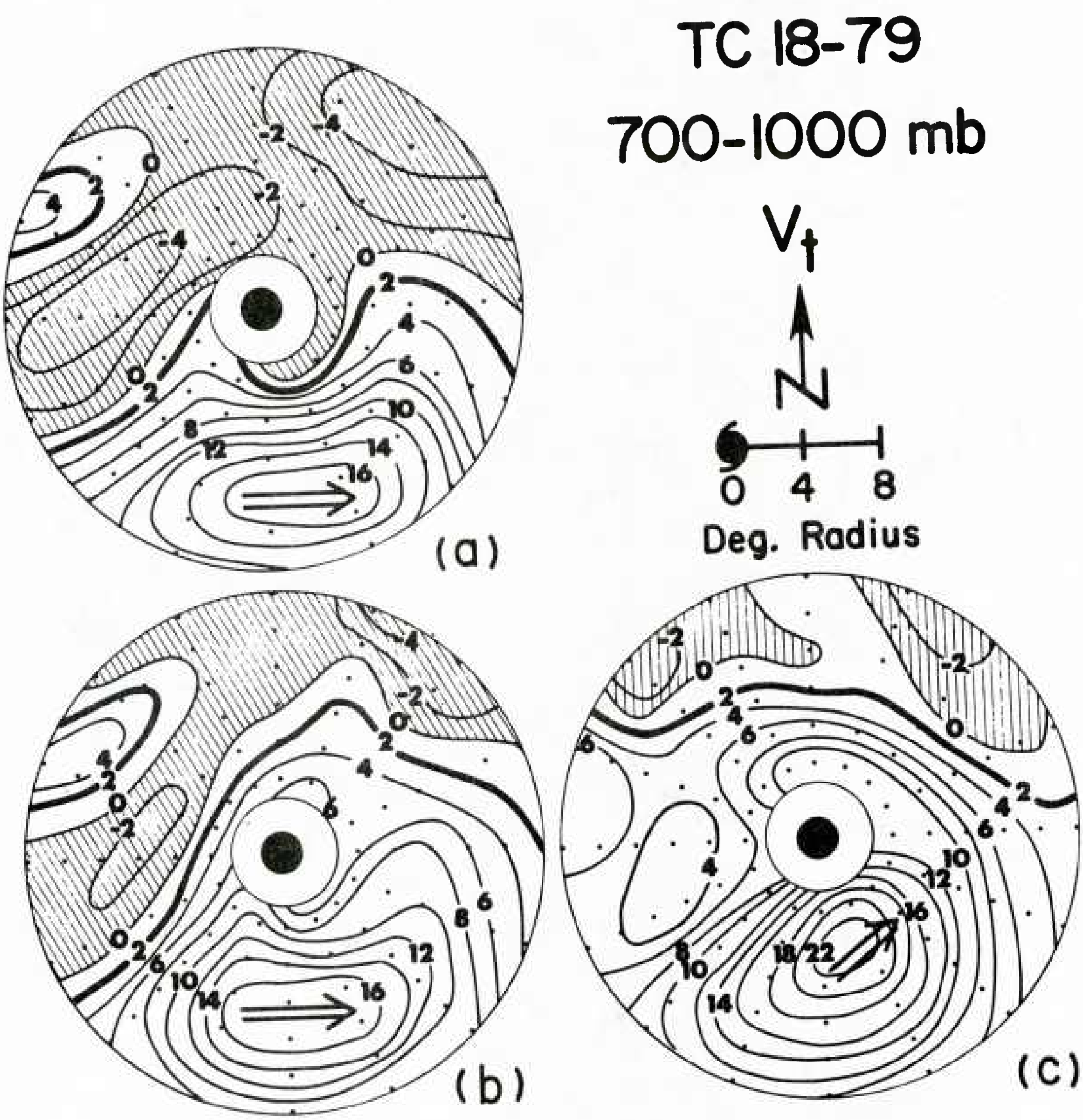

Fig. 3.6. Plan view of low-level circulation (700-1000 mb Vt) in m/s relative to the center of TC 18-79 at 1200 GMT 15 June (diagram a), 1200 GMT 16 June (diagram b), and 1200 GMT 17 June (diagram c) (from Lee, et al., 1986).

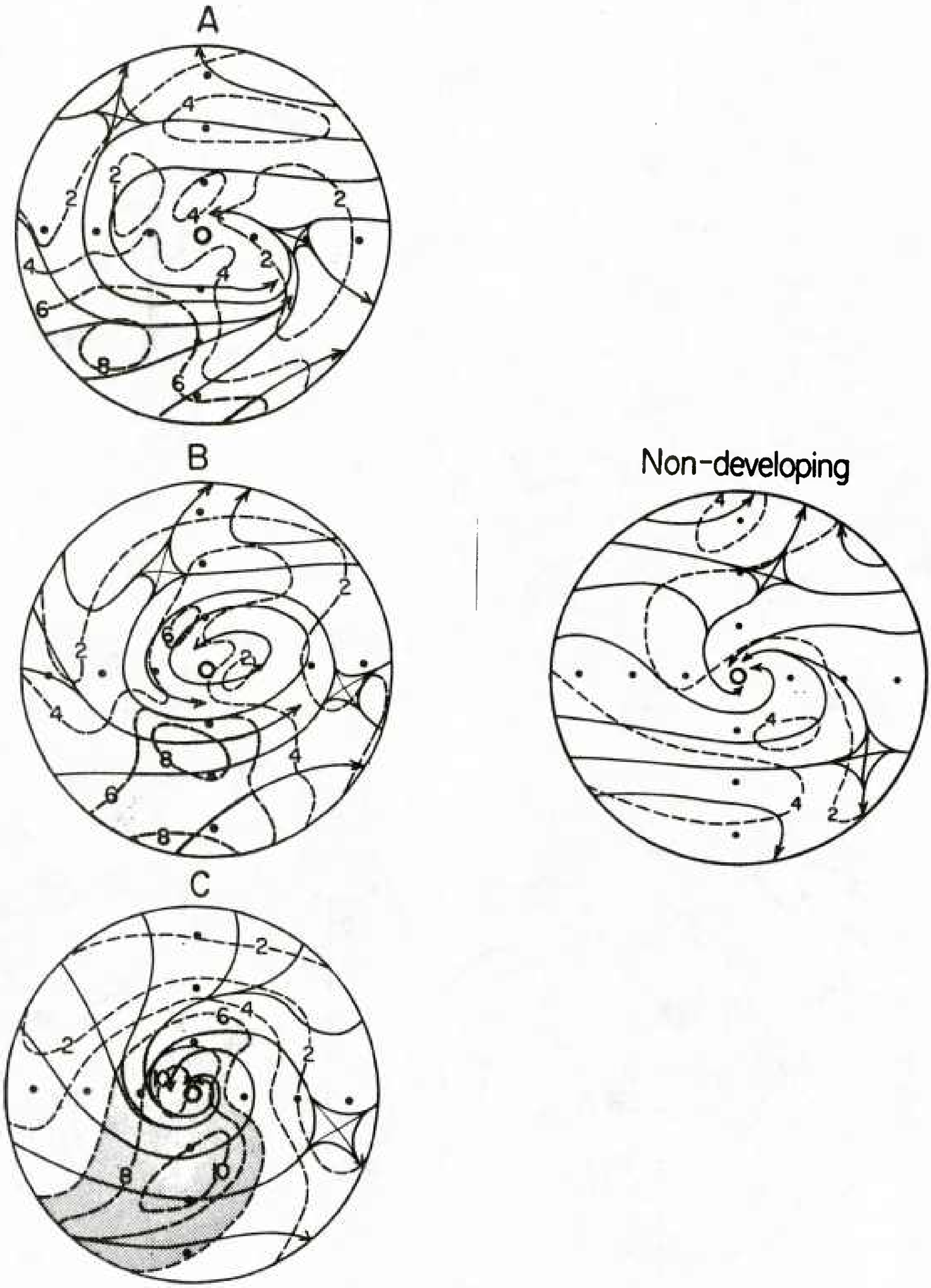

Fig. 3.7. Northwest Pacific plan view 850 mb streamline pattern of rawinsonde composite wind fields surrounding the progressive stages (A, B, C) of early tropical disturbance growth one day apart for developing vs. the same data of an organized tropical disturbance with a prominent cloud cluster system which does not develop into a named tropical storm (diagram on the right) - (from Lee, 1986a).

also given. Note the stronger winds on the southwest side of the developing disturbance at its earliest formation stage and the larger already existing vorticity field at the beginning stage of the cases which develop vs. those cases which do not develop.

f. Wind-Pressure Balance

Recent-year theoretical research on wind-pressure balance relating to tropical storm development problems is indicating that in the tropics, where the Coriolis parameter is small (and the radius of deformation is large), wind-pressure adjustment relationships are such that the pressure field primarily adjusts to the wind field. The wind field tends not to adjust to the pressure field. These external wind surge fields might thus be thought of as a mechanism to induce the observed early pressure decrease which accompanies the developing disturbance.

In earlier years we had thought that the early stage pressure drops of the developing disturbance were a direct result of the disturbance's warming and pressure lowering which accompanied condensation heat release, and that the early wind increases were in response to such pressure decrease. These ideas are no longer believed to be valid for the early stages of tropical cyclone development.

It thus appears that these early stage wind surges on the side of the potentially developing tropical disturbance are a primary mechanism to the disturbance's early stage pressure drop. It seems that this early stage pressure drop then feeds back upon the disturbance and helps in the establishment of the later stage more symmetric circulation and vortex spin-up.

g. Forecaster Responsibility

The TC forecaster should be on the alert for such external forced wind surge action on the sides of potentially developing cloud cluster disturbances. If such wind surges can be detected in the environment and are observed to to be progressing towards one side of the disturbance, then the probability of the disturbance developing into a named cyclone is much higher than it otherwise would be. This is particularly the case if the initial disturbance vorticity before the surge arives is relatively high.

Another powerful influence on tropical cyclone development that should be kept in mind is climatology. If one is in a region and in a season when past year information indicates frequent tropical cyclone development, then the potential of these momentum surges to set off a tropical disturbance's development is much higher than for similar surges about disturbances in seasons or locations whose development is known to be climatologically less frequent.

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4. Structure Variability of Tropical Cyclones

a. Variability in Tangential Wind Profile

Our project's analysis of many hundreds of tropical cyclone radial wind profiles from aircraft (Weatherford, 1985) and many years of rawinsonde information is showing how variable a TC's outer radial wind profile can be for cyclones of similar surface pressure A large variety of different types of inner and outer radius wind profiles can be found. The common practice of classifying a tropical cyclone by its maximum sustained wind speed or its minimum central pressure can frequently be misleading. There are tropical cyclones with small and very intense inner-core circulations but weak outer circulations. There are other tropical cyclones whose central core winds are weak but whose outer circulations are very strong.

It is important that the forecaster try to understand the synoptic conditions that lead to the development of a cyclone with a small and intense inner-core circulation in contrast with those synoptic conditions that bring about the weaker inner core but stronger outer circulation. A cyclone's outer wind strength can be important in determining its net rainfall, the radial extent of 30 and 50 knot winds, and other structural features. Strength of outer winds likely also has an influence on a cyclone's surge potential.

These differences in inner and outer radius wind speed also manifest themselves with respect to the day-to-day changes in the cyclone's radial wind field. When the winds of a TC increase or decrease, they seldom do so evenly. Winds at one radius may become stronger, while a simultaneous wind decrease or no change is occurring at another radius.

b. Definitions

New definitions of the tropical cyclone, which specify outer wind distribution, are fundamental to dealing with these differences in radial wind profiles. We propose that the structure of the tropical cyclone be defined in terms of the magnitude of its tangential wind within the following radial belts: (see Fig. 4.1).

(1) <u>Intensity</u> - highest sustained lower-tropospheric wind speed (usually found between 0-1^{o} radius) or minimum central pressure.

(2) <u>Strength</u> - or <u>Outer Wind Strength</u> - mean lower-tropospheric tangential wind between 1-3^{o} or 1-2 1/2^{o} radius (which are routinely measured by standardized four equally spaced radial leg flight tracks by Guam-based aircraft reconnaissance at 700 mb).

(3) <u>Outer Circulation</u> - mean lower-tropospheric tangential wind between 3-7^{o} radius as measured or estimated from conventional rawinsonde or weather map analysis.

(4) <u>Environment</u> - mean lower-tropospheric tangential wind between 7-15^{o} radius.

Note in Fig. 4.1 that the radial distribution of tangential wind speed of the cyclone represented by curve (b) has a much greater intensity than curve (a), but at 1-3^{o} radius the winds of curve (a) are larger. Such differences in tangential wind profiles are quite common. Analysis of our project's rawinsonde data sets in the Pacific and Atlantic have led to measurements of the tangential winds within the tropical cyclone's outer radial wind in regions (3) and (4).

Tropical cyclone intensity is a regularly measured or estimated quantity. It is used by forecasters and researchers to describe the state of development of the cyclone. Strength is also an important cyclone parameter. Although it can be measured by the Guam

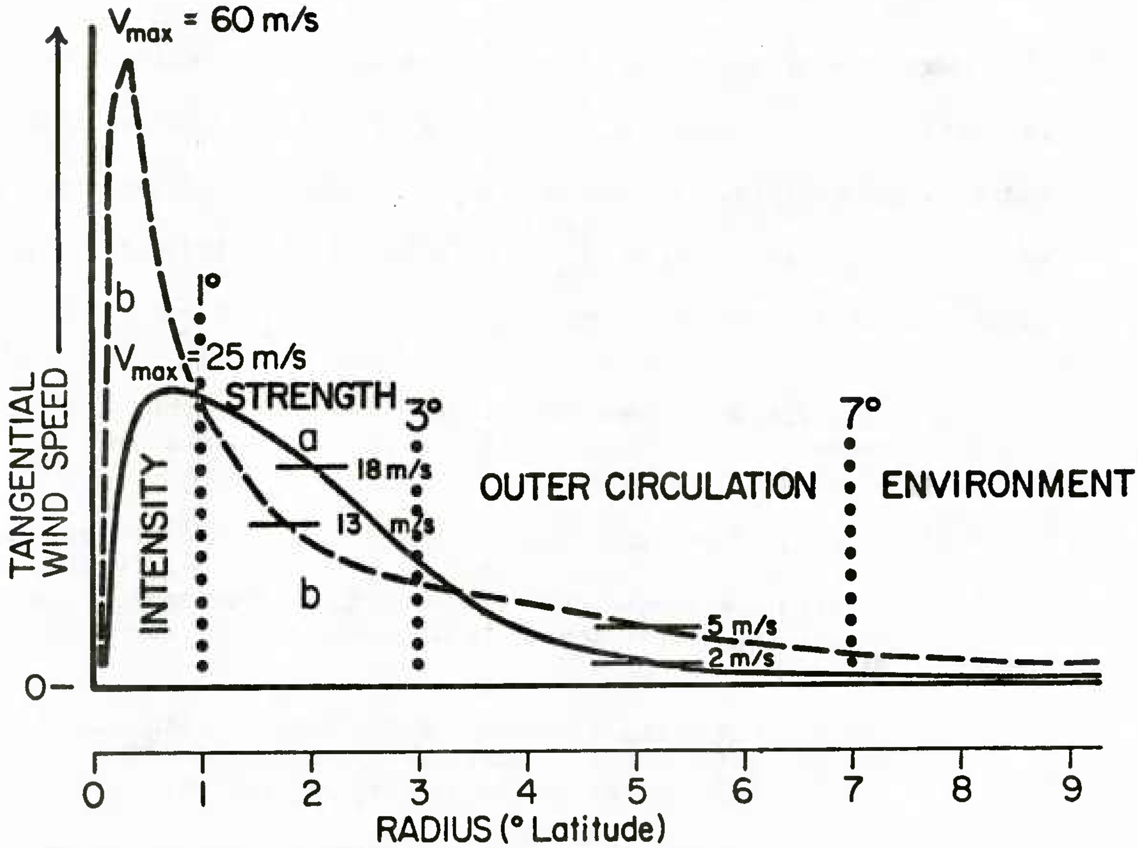

Fig. 4.1. Definition of tropical cyclone intensity, strength, and outer circulation as related to the radial profile of tangential (azimuthal) wind.

reconnaissance flights, it typically is not used by most forecasters. The reconnaissance flights in the Atlantic do not allow its measurement, and the other global storm basins do not make reconnaissance flights.

Our project's recent year research is indicating that tropical cyclone intensity and intensity change is strongly related to the circulation characteristics of the cyclone's upper tropospheric outflow, as discussed in the next chapter. By contrast, the physical processes influencing cyclone strength and strength change are more related to the character of the cyclone's surrounding lower tropospheric environment.

c. Intensity vs. Strength Relationships

Through analysis of the Guam standardized TC reconnaissance flight tracks during the 1980-1982 seasons (see Fig. 4.2), Weatherford (1985) has shown that TC central pressure and outer wind strength (here defined as the mean tangential wind along four radial legs between 1 and 2 1/2^{o} radius) often are not very well related. This is particularly so for the most intense tropical cyclones (see Fig. 4.3). It is also implied that the mean radius (four radial flight leg average) of 30 knot and 50 knot surface winds can undergo a similar large variation between different cyclones of similar central pressure and at different times within the same cyclone. See Figs. 4.4 and 4.5.

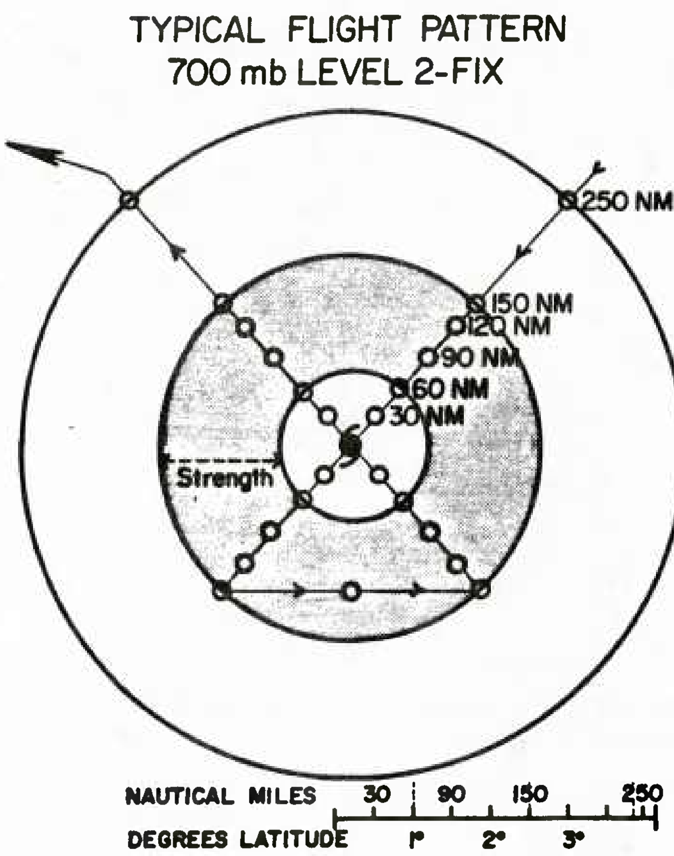

Fig. 4.2. Typical 700 mb flight pattern - range marks denote required observation points (stippled area encloses 'strength') (from Weatherford, 1985).

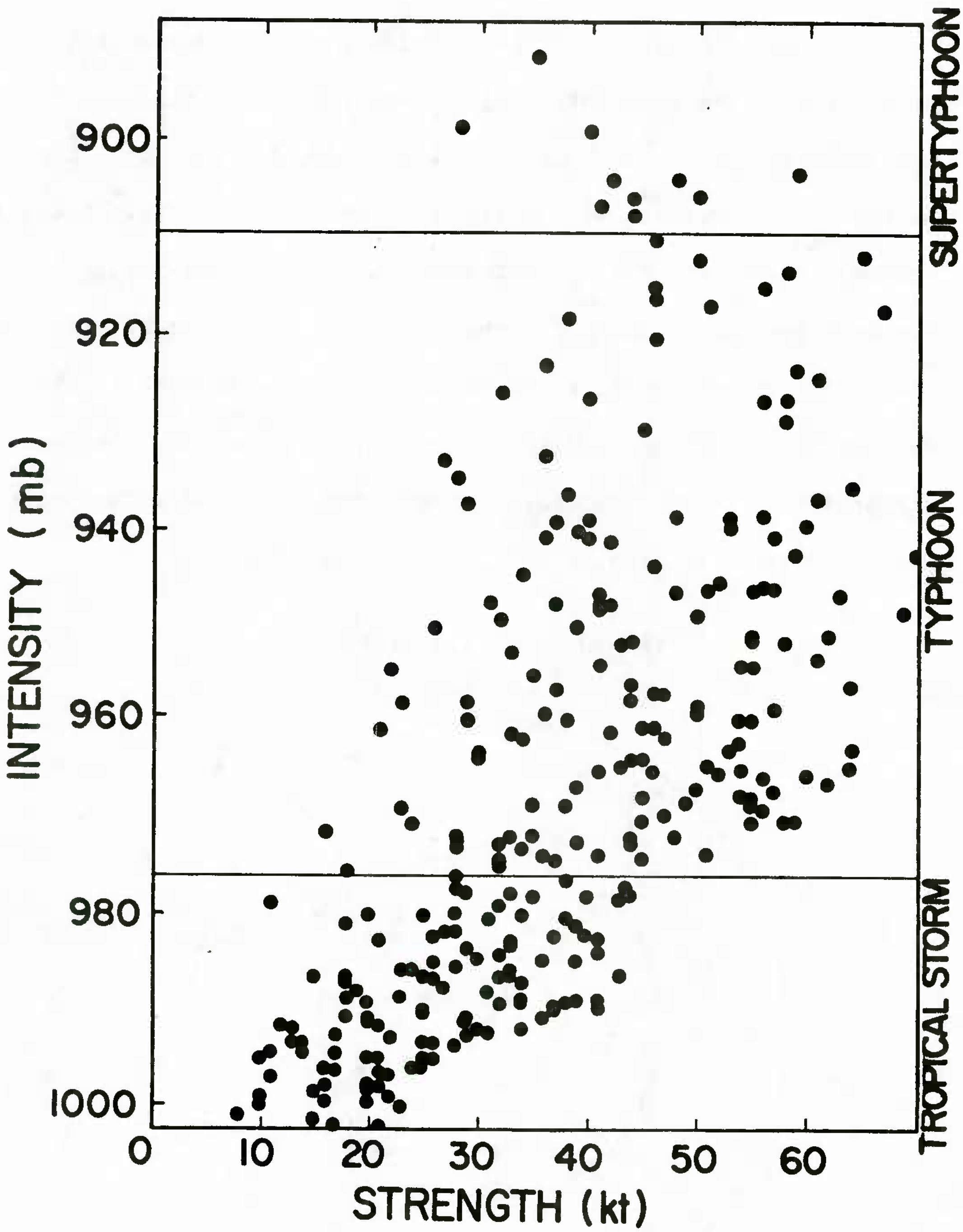

Fig. 4.3. Intensity (minimum sea-level pressure) versus strength scatter diagram (from Weatherford, 1985).

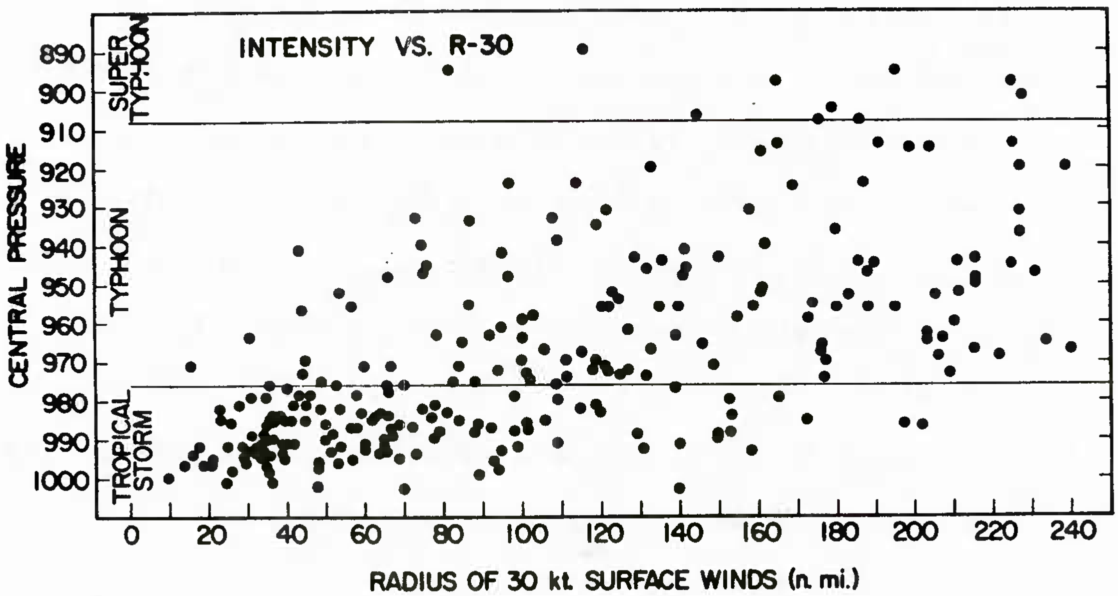

Fig. 4.4. Intensity (minimum sea-level pressure) versus the radius of 30 kt wind speeds shows large scatter (from Weatherford, 1985).

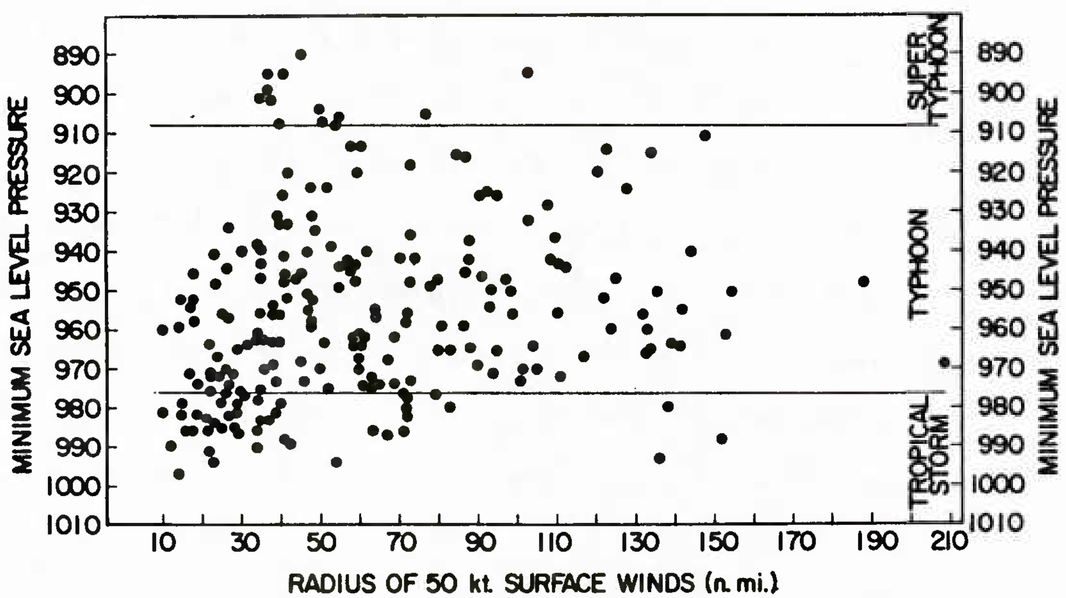

Fig. 4.5. Intensity (minimum sea-level pressure) versus the radius of 50 kt wind speed (n mi) scatter diagram (from Weatherford, 1985).

It is important for the forecaster to realize that such large variations in inner to outer radius wind can occur in cyclones of similar central pressure, and that a standardized formula for estimating a cyclone's radius of 30 and 50 kt surface winds based solely on central pressure or maximum wind speed may often give a poor estimate. A forecaster should always try to obtain direct measurements or other implied information concerning the strength of the TC's outer circulation in a way suggested by Holland (1980). He/she should employ estimates of the outer circulation from the central pressure or maximum wind alone only when outer wind information, eye-wall size and satellite cloud shield information are unavailable.

The outer circulation of a tropical cyclone appears to be related to the low level environment in which the cyclone has formed or into which it moves. If there is a very strong and broad monsoon trough in which the tropical cyclone has developed, then the outer circulation, on average, tends to be stronger than the central pressure would indicate - particularly in the cyclone's development period to maximum intensity. The radial extent of the tropical disturbance's deep convection also can be used as an approximate indication of outer wind strength. The broader the cloud shield the generally broader will be the TC's outer radius wind velocities. This is discussed in Chapter 6. There is more conservatism in the outer circulation of the tropical cyclone than the inner circulation. A cyclone's outer circulation cannot change nearly as rapidly as can its inner core eye-wall central pressure and maximum wind speeds.

d. Tropical Cyclone Size

The size and intensity of a tropical cyclone also are not well related. Tropical cyclone size is defined as the mean radial extent of outer tangential winds. This can range from values as broad as 1 to 12^{o} or more. Large differences occur between cyclones. For instance, Hurricane Tracy which struck Darwin, Australia in 1974, and Supertyphoon Tip which occurred in the northwest Pacific in 1979 are contrasting examples. Though its peak winds were about 130 knots, Hurricane Tracy had gale force winds (17 m/s) over an area of only 100 km across. Supertyphoon Tip, on the other hand, although of similar intensity to Tracy, had gale force winds speeds over a 2200 km diameter, an area hundreds of times larger than Tracy. Figure 4.6 shows two examples from the Atlantic basin. Hurricane Camille had estimated maximum winds of about 170 knots, while Faith, though much larger, had maximum winds of only about 50 m/s.

Merrill (1984) has performed a statistical analysis of tropical cyclone size as a function of cyclone intensity. He found that the size of a tropical cyclone is very much related to the width of the environmental cyclonic circulation in which the cyclone forms or into which it moves. Cyclone size is, however, only weakly correlated (only ~ 0.3) with the cyclone's maximum sustained wind speed or central pressure. This means that only about 10% or less of the variance of the tropical cyclone's central-core intensity can be attributed to the radial extent of its outer circulation (see Figs. 4.7 and 4.8). This lack of much of a direct relationship between tropical cyclone intensity and size is generally known by experienced forecasters but was not well documented until Merrill's analysis.

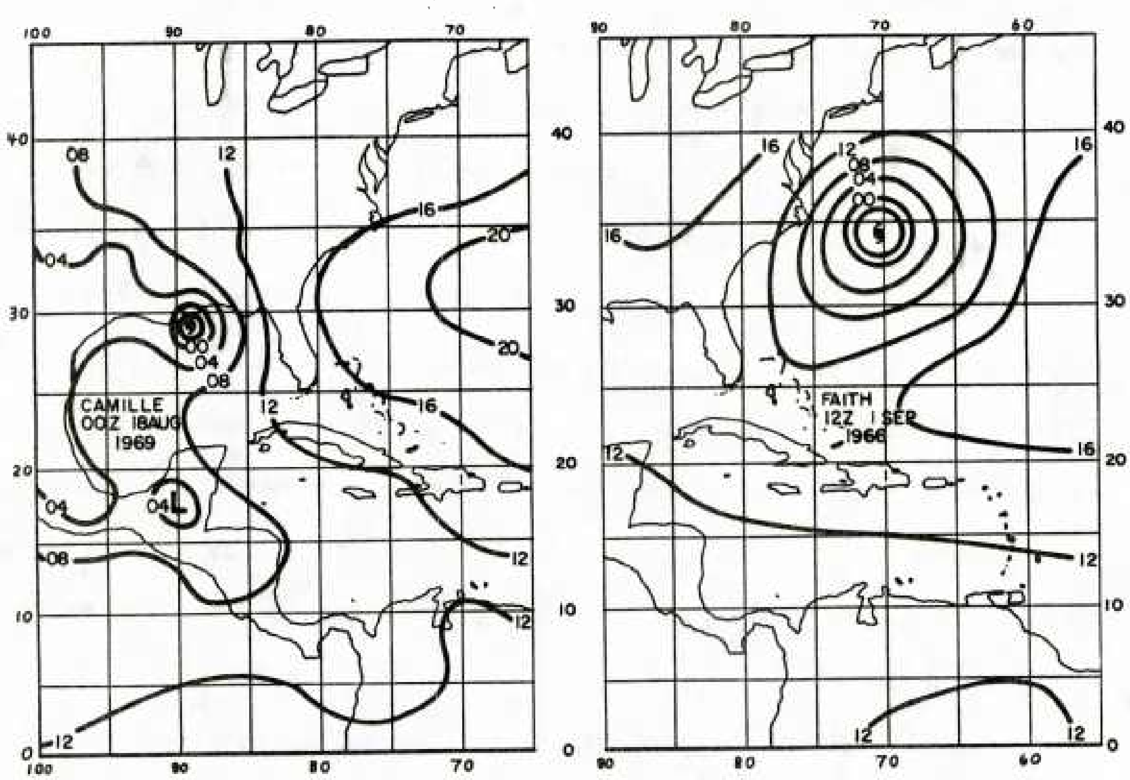

Fig. 4.6. Surface pressure analyses for Camille, a small, intense hurricane (left) and Faith, a larger but weaker one (right) (from Merrill, 1984).

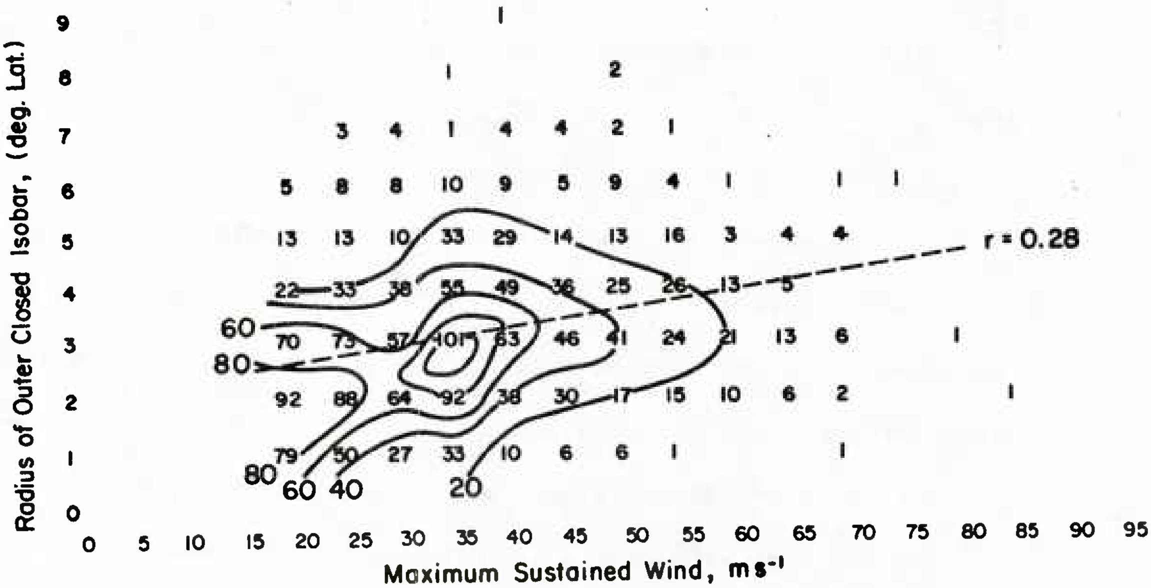

Fig. 4.7. Tropical cyclone size as a function of maximum sustained wind for Atlantic tropical cyclones, 1957-1977. Observations are tabulated in classes of 1° latitude and 10 kts. The least square line is fitted to the raw data (from Merrill, 1984).

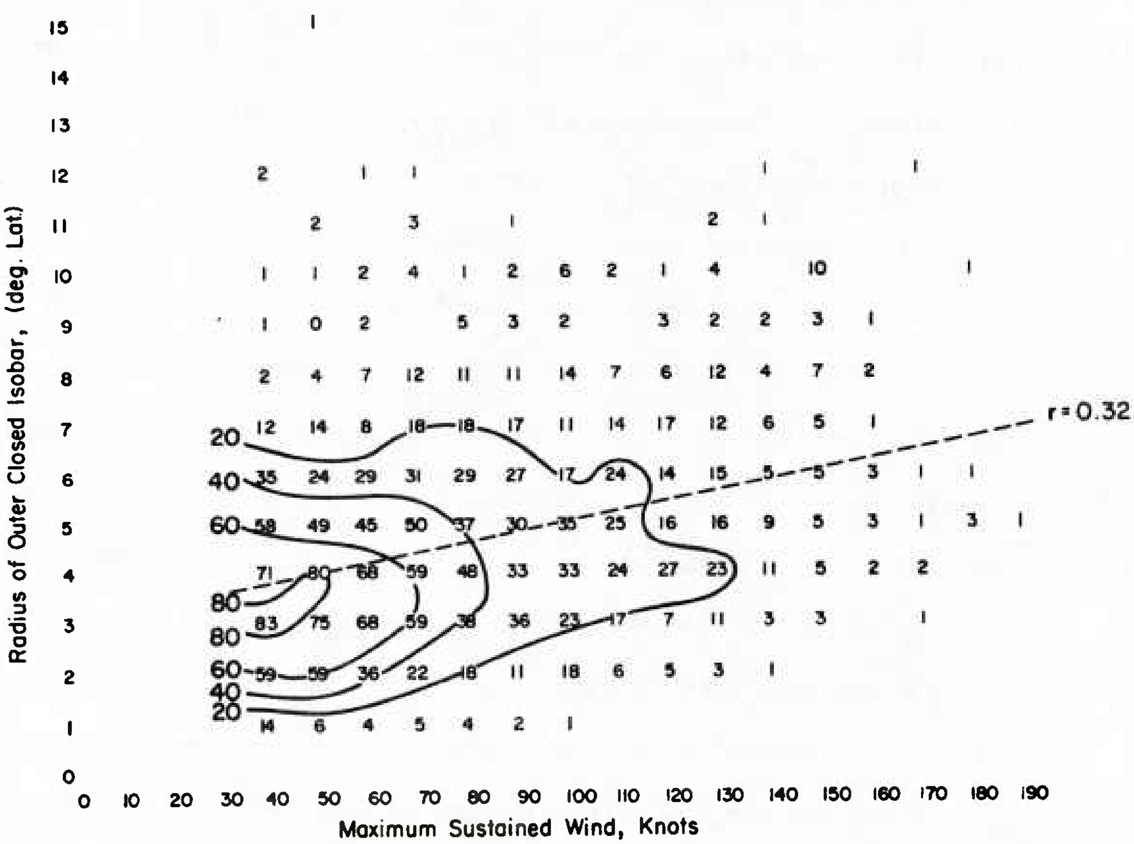

Fig. 4.8. Same as Fig. 4.7 except for Pacific tropical cyclones (from Merrill, 1984).

Forecasters should also be prepared to find a wide variation in the mean radius of 30 and 50 knot winds between cyclones of similar central pressure.

e. Eye Size vs. Intensity and Strength

There is, as well, a large variation in eye-wall radius among cyclones with comparable minimum central pressures. Figure 4.9 portrays three years (1980-1982) of NW Pacific eye-wall variations as analyzed by Weatherford (1985). By itself the size of a TC's eye does not have much of an observable relationship with a cyclone's minimum pressure. A decreasing eye size with time is, on average, associated with a decreasing sea level pressure, however. Similarly, an increasing eye size, on average, is associated with a cyclone losing intensity. But these are only average conditions. Weatherford (current research) has a number of individual cases which show eye-wall clouds expanding as intensification is occurring and the opposite condition.

Tropical cyclone strength (mean tangential wind between 1-2 1/2° radius) also does not have very much of a direct statistical relationship with eye size, but does have a notable relationship with the combination of eye size and minimum pressure. The smaller a cyclone's eye, the generally weaker will be its outer radius tangential winds for a given central pressure. Conversely, the larger the eye, the generally stronger will be the cyclone's outer winds in comparison with another cyclone of similar central pressure but smaller eye. Figure 4.10 demonstrates this relationship. Note that although there is a rather broad scatter of points, a clear statistical relationship exists for cyclones to have stronger outer circulations if they have larger eyes or no eyes in comparison with other cyclones of similar central

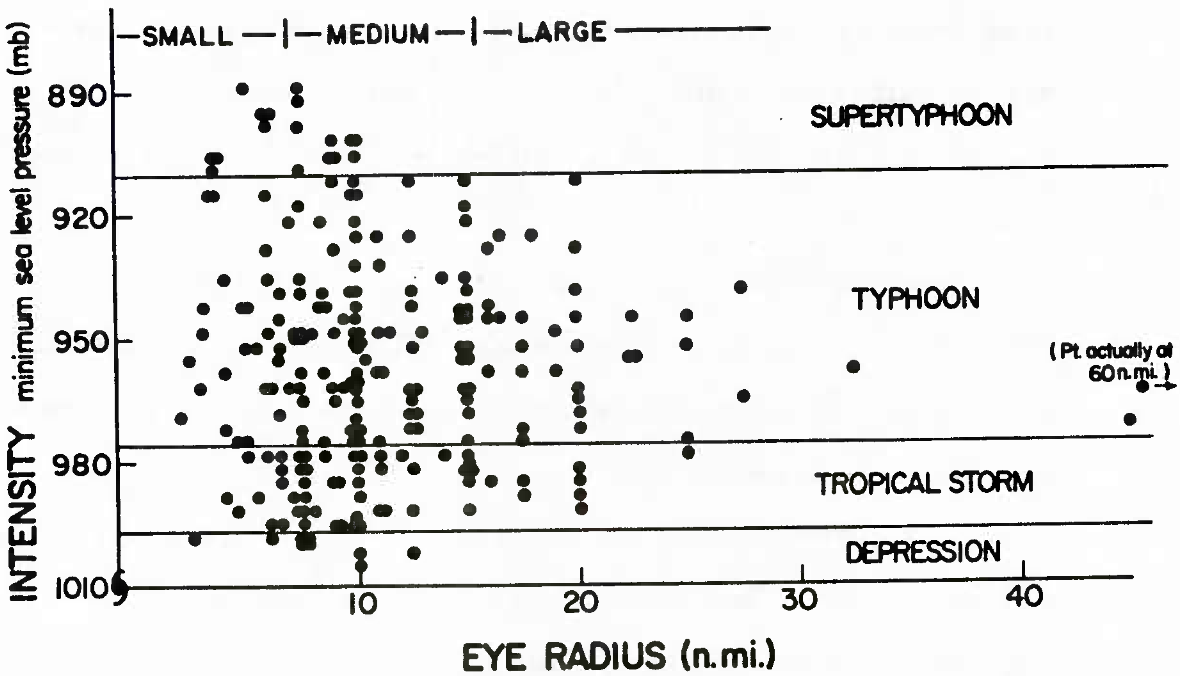

Fig. 4.9. Eye size vs. intensity (from Weatherford, 1985).

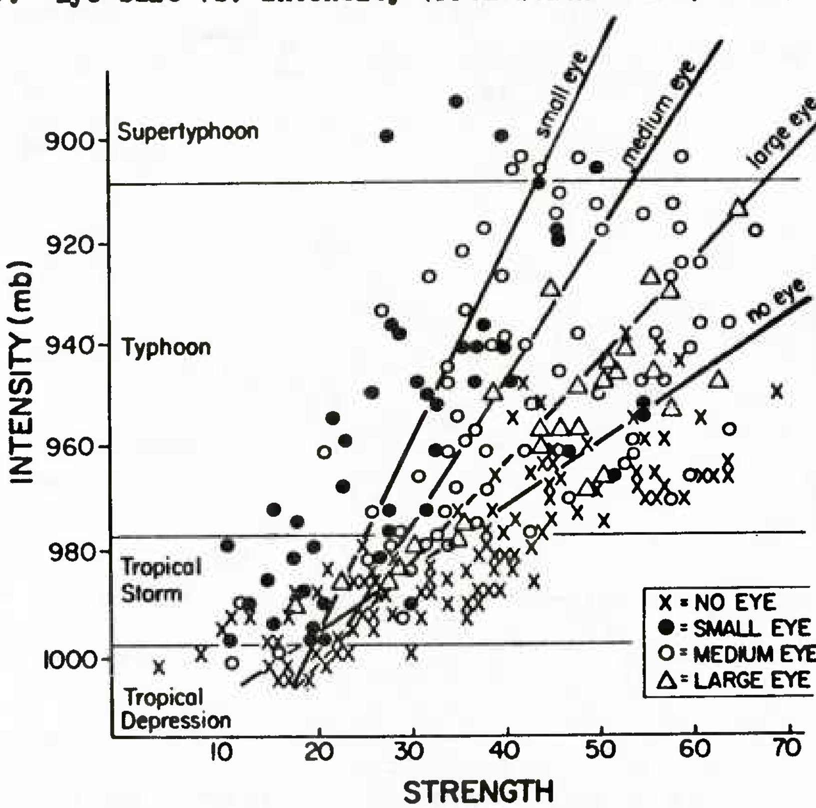

Fig. 4.10. Intensity versus strength differs by eye class (small eye 0-7.5 n mi; medium eye 7.5-15 n mi; large eye 15-60 n mi) (from Weatherford, 1985).

pressure but which have smaller eyes. Or put the opposite way, a cyclone with a small eye will typically have a weaker outer circulation than another cyclone of similar central pressure which has a large eye or no eye (see Fig. 4.11).

Forecasters who do not have outer radius wind information can likely improve their outer radius wind estimates if they take this statistical relationship into account and combine information on eye size and central pressure.

It is important that the TC forecaster have a good grasp of the wide variety of TC structural characteristics which can occur between cyclones of similar central pressure.

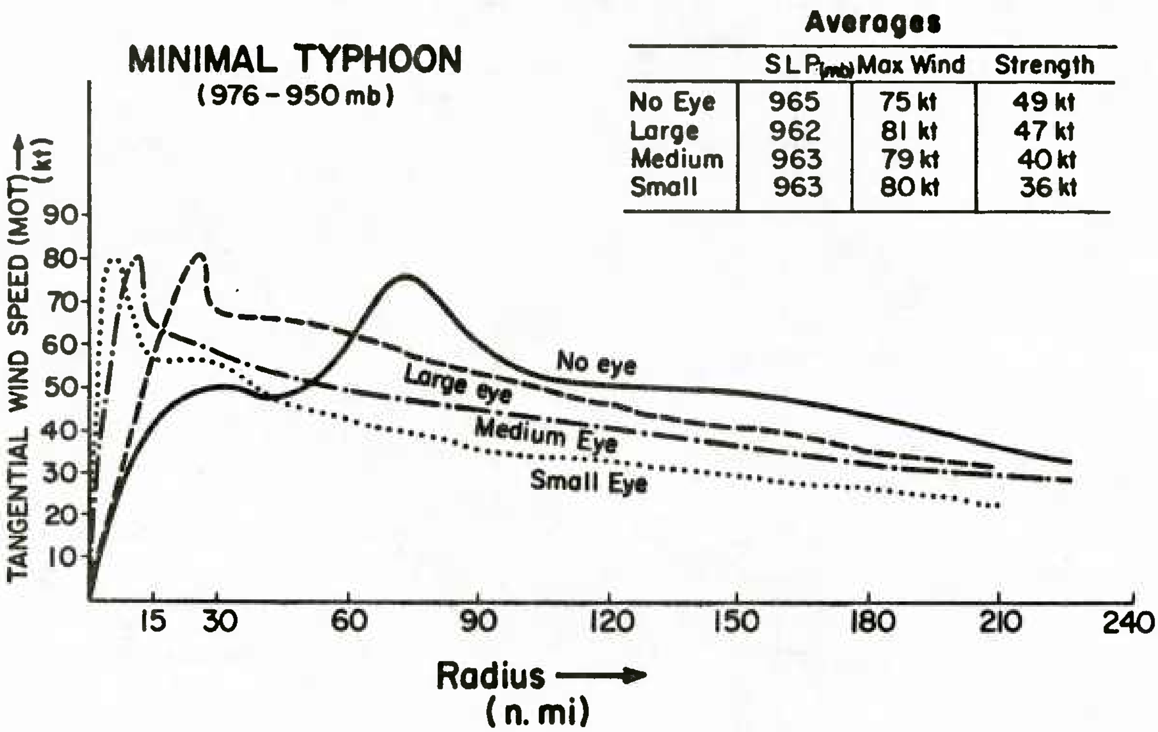

Fig. 4.11. Average wind profiles by intensity class show how different the profiles can be given the eye class for: (a) the tropical storm, (b) the minimal typhoon, (c) the intermediate typhoon and (d) the extreme typhoon (from Weatherford, 1985).

f. Diurnal Variations

Our analysis of three years of Guam TC aircraft reconnaissance data and 21 years of rawinsonde composite data shows no evidence of any systematic diurnal variation in cyclone tangential wind speeds. Figure 4.11 shows Guam aircraft measured daytime vs. nighttime radial profiles of tangential wind speed for four TC intensity classes. No systematic diurnal wind variations are observed. Similarly our 00Z vs. 12Z rawinsonde compositing at radius of 2, 4, and 6° radius in the northwest Pacific and Atlantic shows no systematic diurnal tangential wind differences (see Figs. 4.12 and 4.13). Rainfall measurements over many years from western North Pacific atolls (see W. Frank, 1976) also do not indicate any appreciable diurnal differences.

These measurements are at odds with diurnal measurements of IR satellite observed cloudiness and daytime visual cloudiness in the Atlantic and northwest Pacific where a systematic afternoon maximum (~ 20 to 40% greater in the 24-hour daily average) has been reported by a number of researchers. Tropical cyclone forecasters should not interpret these satellite observed diurnal cloudiness variations as an indication that the tangential wind speed of a TC has a comparable diurnal variation.

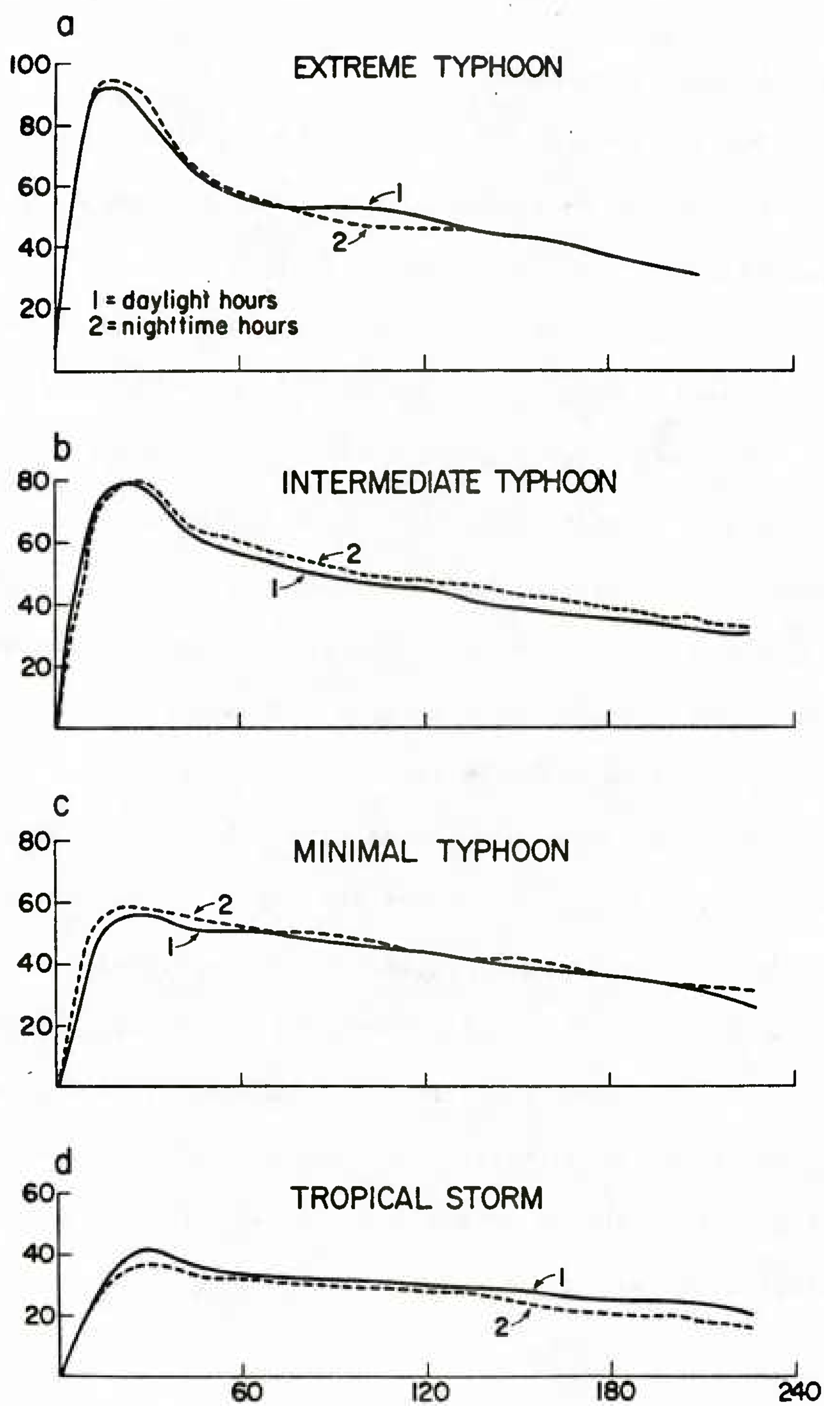

Fig. 4.12. The diurnal profiles by intensity class. Solid curves represent data gathered between 00 to 12Z, dashed curves between 12 to 24Z (nighttime hours 21 to 09 LT). Intensity classes are as follows: extreme typhoon, below 920 mb; intermediate typhoon, 920-950 mb; minimal typhoon, 950-976 mb; tropical storm, 977-999 mb (from Weatherford, 1985).

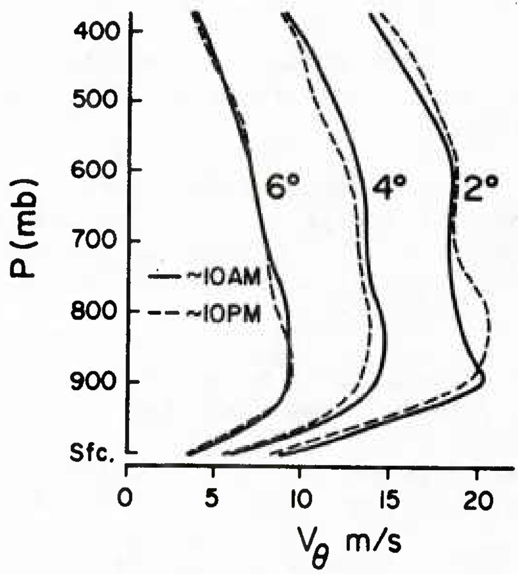

Fig. 4.13. Vertical profile of 00Z (10 AM) and 12Z (10 PM) tangential winds at 2, 4, and 6^{o} radius for west Pacific typhoons (from Gray, 1981).

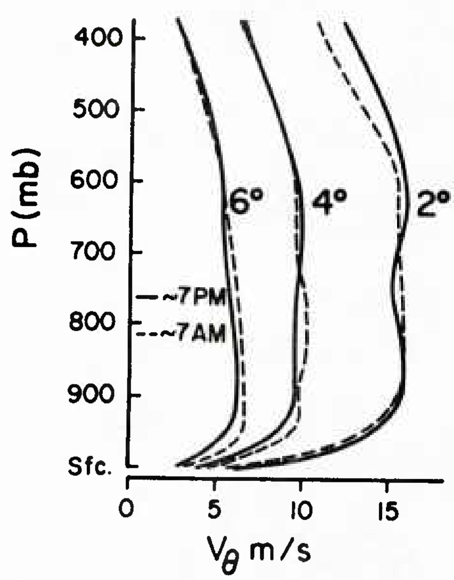

Fig. 4.14. Vertical profile of 00Z (7 PM) and 12Z (7 AM) tangential winds at 2, 4, and 6^{o} radius for west Atlantic hurricanes (from Gray, 1981).

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5. Tropical Cyclone Intensity Change

a. Background

Intensity change is the most important and yet most difficult and challenging TC structural feature to forecast. Intensity change forecast skill is presently very low. This is because we still don't have a thorough grasp of all of the physical processes which are responsible for tropical cyclone intensity change. And, even if we did have such a grasp, it would be difficult to observationally measure those features which would likely be required for the making of an accurate forecast. Nevertheless, significant progress, which may be of value to the forecaster, has recently been made on this topic.

Observational evidence within the inner core of the tropical cyclone from aircraft reconnaissance and eye dropsondes indicates that tropical cyclone intensity and intensity change is, in general, proportional to the magnitude of the dynamically forced subsidence warming within the cyclone eye (or central region if no eye should be present). The strength of this central core subsidence appears, to a large extent, to be directly related to the intensity of eye-wall deep convection and inversely to the radius of the eye. For equal intensity eye-wall convection and the smaller the radius of maximum convection, then (a) the smaller the eye; (b) in general, the more intense the subsidence warming; and (c) the lower the pressure drop. An increase in tropical cyclone intensity is typically accompanied by an increase in eye-wall (or central cyclone) deep convection and a consequent increased forced subsidence as idealized in Fig. 5.1. Arnold's (1977) Colorado State University composite satellite study gives evidence of systematic

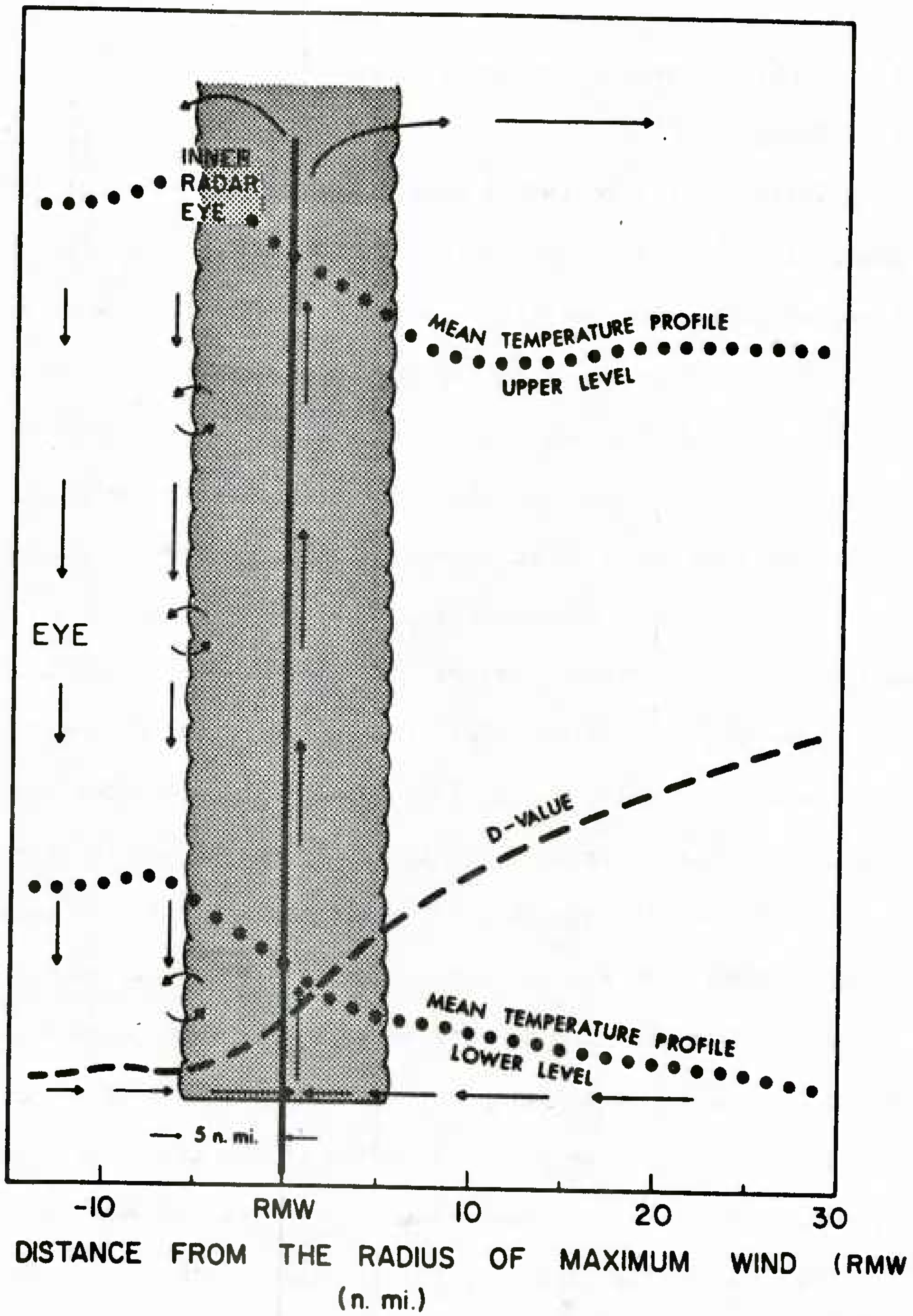

Fig. 5.1. Idealized portrayal of the mean flow conditions in the hurricane's inner core region. The horizontal and vertical arrows represent the radial and vertical velocities, respectively. Mean D-value (or pressure-height curve) and temperature profiles are as indicated (from Shea and Gray, 1973).

inner-core deep convection increases during the progressive developmental stages of a cloud cluster to super typhoon stage, as do Dvorak's (1975, 1984) intensification techniques. This inner core convective concentration goes on irrespective of the overall amount of deep convection within the entire cyclone system.

The mode of evolution of the cyclone's inner region deep convection is important, however, in determining how the cyclone's inner deep convection can be maintained. In general, deep Cb convection acts to warm and to stabilize the upper troposphere. All tropical cloud clusters with deep convection have warm upper tropospheric layers. Such upper level convective stabilization, if continued in the central area of the tropical cyclone for very long, would be expected to stabilize and reduce future deep convection. If such stabilization were to occur within the cyclone eyewall, convection would eventually weaken the eye subsidence and intensification would halt. A general cyclone filling would occur. Previous CSU research (Gray and Shea, 1973) indicates that the eye of the tropical cyclone is dynamic. It typically ventilates itself every 4-8 hours or so. Intensity is reduced in cyclones that cannot maintain continual eye subsidence. This requires vigorous and continuous eye-wall convection.

b. Vertical Stability of Eye-wall Convection

We know that TC intensity change is primarily involved with the increase and/or maintenance of deep Cb convection within the cyclone's inner-core ($r < 1^{\circ}$ radius) circulation. This inner-core deep Cb convection is, of course, directly related to the cyclone's inner-core mean in-up-and-out vertical circulation. The mean in-up-and-out vertical circulation causes tangential wind spin-up beyond that required to balance frictional dissipation. Meteorologists agree that inner-core tangential wind spin-up can only occur through an enhancement or a maintenance of inner-core deep convection. There is, however, no well established technique for forecasting such inner-core deep convection. It is the forecast unknown. We do, however, accept that there are two physical requirements needed to maintain the conditional lapse-rate buoyancy of the inner-core which allows such deep convection to continue:

1) The θ_e of the inflowing boundary layer air must be increased as much as possible or at least enough to match the inner-core warming of the upper troposphere. This depends upon isothermal expansion of the inflowing boundary layer air as it blows toward the lower pressure of the storm center. This results in sizable surface energy flux which is directly dependent upon the cyclone's underlying sea-surface temperature (SST).

2) The upper levels of the cyclone's inner-core must be kept as cool as possible - this is related to the upper level vertical wind shears in the inner-core region being as small as possible. The inward warming due to thermal wind requirements is thus reduced.

<u>With regard to requirement 1</u>), tropical cyclones intensify most rapidly in selective regions such as the area northwest of Guam where SST are usually very high. As discussed by Merrill (1985), TC intensity change is favored by SST being as high as possible. Merrill's analysis indicates that SST sets an upper limit on the intensity to which tropical cyclones can go but does not specify the intensity they actually will reach - see Fig. 5.2. High SST permits the low level inflowing air to reach the cyclone's inner-core with a higher value of θ_e than would otherwise be possible if the sea surface were colder. SST above 26°C are thus a necessary but not a sufficient condition for

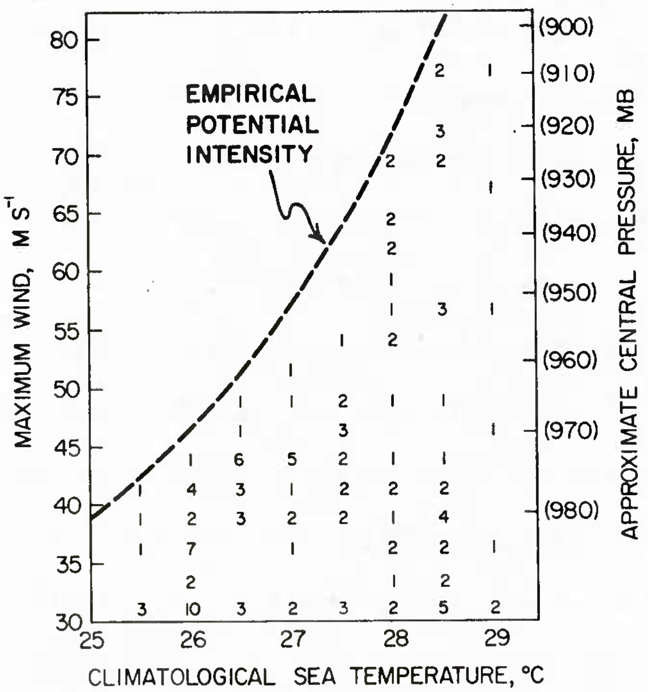

Fig. 5.2. Empirical relationship between sea surface temperature and best-track maximum wind for the sample of 5 years of Atlantic hurricanes. The dashed line is an empirical upper bound on intensity as a function of SST (from Merrill, 1985).

intensification. Other factors besides high SST are also important. Were these other factors all the same, however, then cyclone intensification would likely be directly related to SST.

<u>With regard to requirement 2</u>), thermal buoyancy requires that the temperature of the cyclone's inner-core (radius < 1-2^{o}) upper troposphere be as cold as possible. The colder the inner-core upper troposphere is, the larger will be the convective instability conditions. From a thermal stability point-of-view, eye-wall convection can continue only as long as the upper level of the inner-core does not warm faster than the low level air can increase its temperature and moisture. Those processes which act to inhibit such upper level eye-wall warming are very important to the intensity change process. It appears that the characteristics of the tropical cyclone's outflow

channels have an important relationship to a cyclone's upper level warming processes and thus its intensification potential.

The stronger and more concentrated the TC's outflow channels and the more effective their evacuation of negative tangential momentum, the more favorable can be an associated inward positive tangential momentum flux between such upper layer channels. If significant inward tangential momentum flux can come into the TC at upper layers, then upper level vertical wind shears will remain smaller and the upper level inner-core warming which normally accompanies cyclone intensification will be held to a lower value than would otherwise occur. Inner-core deep convection can then more easily be maintained. Intensification is then more likely.

c. Colder Temperatures Aloft and Association with Stronger Upper Level Tangential Winds

New rawinsonde composite and individual case analysis on our project (as initially reported on by R. Edson, 1985) is showing that intensifying tropical cyclones have, on average, colder temperatures between 100-200 mb than do non-intensifying systems of the some central pressures. Maximum anomaly is at 125 mb (see Figs. 5.3 and 5.4). These temperatures are the major differences we are able to detect between intensifying and non-intensifying cyclones of the same central pressure. Individual soundings can show greater cooling. These colder temperatures indicate that there is, in general, a smaller inner-core upper tropospheric lapse-rate stability in tropical cyclones that intensify than for those that do not. In many cases, lapse rates between 350-125 mb are only slightly more stable than the dry-adiabat. If significant freezing is hypothesized to occur in the deep Cb

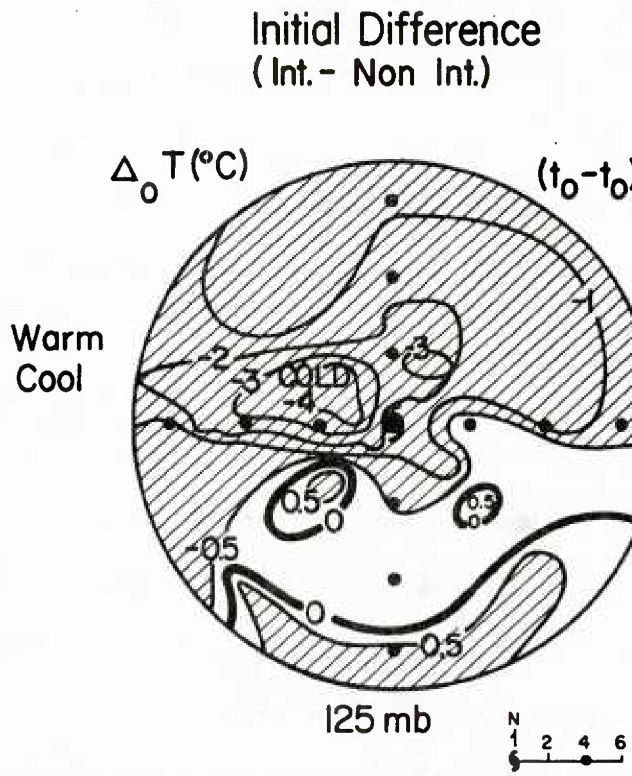

Fig. 5.3. Plan view of the difference in temperature at 125 mb between intensifying minus non-intensifying TC of the same initial central pressure. Intensifying systems are colder than non-intensifying systems (from Edson, 1985).

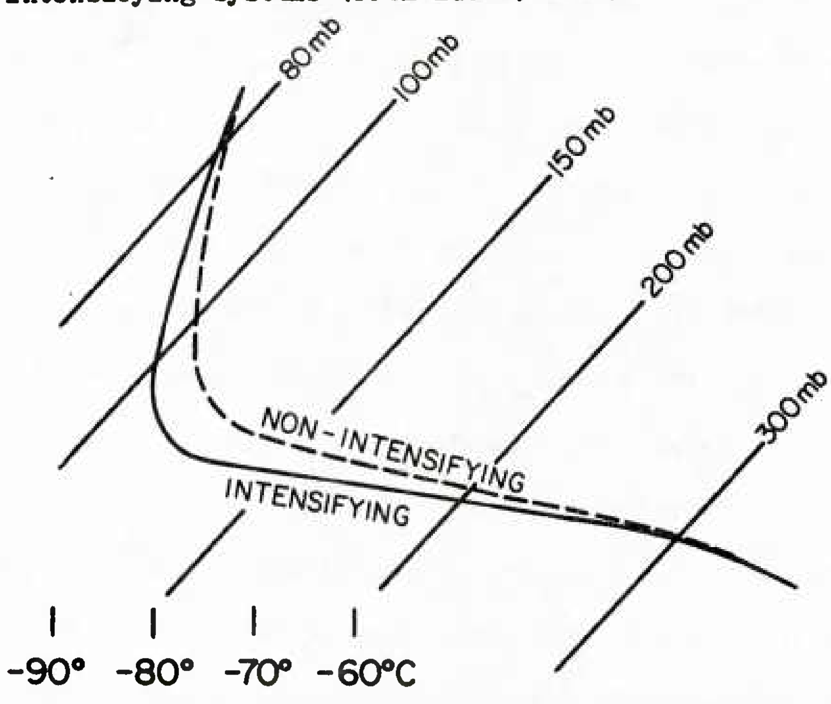

Fig. 5.4. Tephigram plot of upper tropospheric temperature of 0-2° radius soundings of intensifying vs. non-intensifying cases when central pressures at the start of intensification or non-intensification are the same (adopted from Edson, 1986).

convective elements, then conditions approaching close to free convection appear to be possible within the upper levels of the intensifying TC.

Our 21-year rawinsonde composite analyses of all upper-air soundings which are available between 1-2^{o} and 2-3^{o} radius (as close as we have reliable data) of intensifying and non-intensifying TC cases is also showing significantly larger tangential winds at the upper levels of intensifying cases in comparison with non-intensifying cases of the same central pressure. These greater tangential winds with the intensifying cyclone appear to be associated with upper level horizontal momentum imports (125-200 mb) into the cyclone's inner-core from its environment. These upper level inward tangential wind transports act to further enhance tangential momentum increases as a result of the accompanying extra 250-400 mb inflow resulting from the increase in upper level convection. A Doppler radar vertical motion study of TC inner-core convection by Marks and Houze (1985) has documented some cases of a secondary maximum in upper level vertical motion within the TC's inner-core region of deep convection. We think that this may be a common feature of intensifying systems.

d. Physical Processes Occurring Within the TC's Eye and Eye-wall Region

The more positive the 150-300 mb eye-wall to 2^{o} radius tangential winds, the generally smaller is the vertical shear of tangential wind between 400-150 mb and the less the requirement for an associated large thermal wind inner core horizontal temperature gradient to balance such vertical shear. This acts to maintain less stable inner-core lapse rates than would otherwise be possible if larger tangential vertical shears were present.

The author and a number of his research colleagues believe that the tropical cyclone's inner core upper troposphere is prevented from warming up to the point of vertical stabilization (and the cutting off of inner-core deep convection) by the presence of very strong and concentrated upper tropospheric (i.e., 125-250 mb) horizontal outflow channels to the cyclone's environment. These outflow channels advect out anticyclonic momentum and appear to cause (the physical processes are not yet well understood) a partial mass compensating inward transport of more positive tangential momentum. This acts to establish and maintain a higher tangential wind within the upper levels of the TC's inner-core than would otherwise be possible.

To maximize a cyclone's central pressure drop and to minimize buoyant stabilization, it is important that the convectively induced warming outside the subsidence eye region occur as high as possible in the troposphere. This maximizes surface pressure decrease and minimizes upper level wall cloud temperature. It is necessary that the cyclone's eye be as warm as possible but that the upper troposphere of the eye wall cloud (or the core convection region if there is no eye) be as cool and thus as unstable for deep convection, as possible - see Fig. 5.5.

The lower the cyclone pressure the warmer (hydrostatic) the eye must become. The warmer the eye, the stronger must be the dynamically forced subsidence and the eye-wall or core deep convection which is necessary to drive it. The higher up the wall cloud warming occurs, the less the buoyant stabilization of the upper and middle levels of the

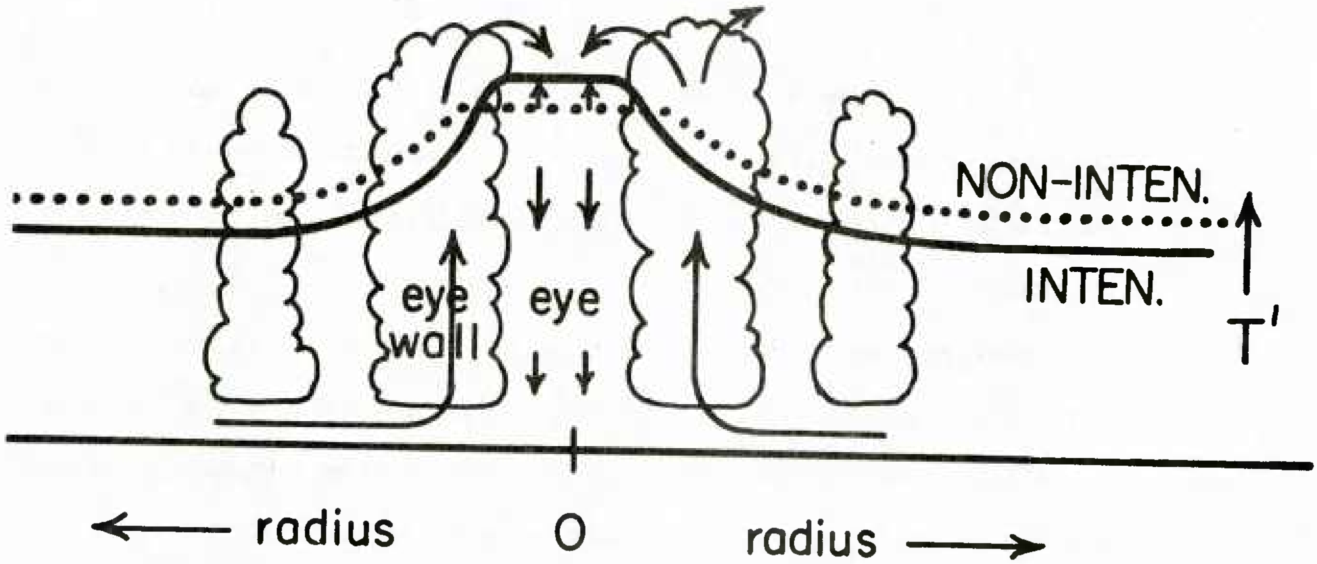

Fig. 5.5. Temperature deviation (T') within the eye and eye-wall cloud which occurs with TC intensification vs. that for non-intensification. Note that the eye-wall cloud of the intensifying cyclone is colder than the non-intensifying system.

wall cloud and the greater the pressure thickness change which can occur for a given amount of warming.(1)

One of the distinctive features of the tropical cyclone's inner core region is the intense horizontal temperature gradient at the eye-wall. Approximately two-thirds of the temperature increase from the storm's outer environment to the center of the eye typically occurs within the eye-wall cloud (see Fig. 5.1). The colder the upper levels of the eye-wall cloud are in comparison with the eye's center, the more intense can be the eye-wall convection and the greater the dynamically forced subsidence within the eye. Intensification usually requires that there be a strong temperature gradient of the eye-wall cloud.

The larger the cyclone's inner core upper-tropospheric cyclonic

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(1) For similar amounts of temperature (ΔT) increase between equal pressure layers (ΔP), larger thickness are obtained if such warming occurs at higher than at lower levels.

tangential circulation becomes, the generally larger will be its eye-wall pressure drop (for a given amount of warming) and the less will be the stabilization at upper middle levels. Future deep convection will be more likely.

It should be realized that the well-developed tropical cyclone has cyclonic flow at all levels in its inner core. Figure 5.6 illustrates a typical 200 mb pattern with anticyclonic flow at outer radii and the usual cyclonic flow at inner radii.

New wind compositing research at CSU (Edson, 1985; Merrill, 1985) is showing that intensifying tropical cyclones are best distinguished from non-intensifying (or less intensifying) cyclones by their increasing tangential wind velocity in the upper troposphere at inner radii of 1-3° and less - and by their colder temperatures - See Figs. 5.7 and 5.8. Cylindrical thermal wind balance considerations dictate that intensifying cases have less buoyant stability near the cyclone's core (but not in the eye) when the upper tangential winds are more like curve (a) than curve (b) in Fig. 5.9. Thermal wind requirements would also dictate that there be much more warming outside the eye between the levels of 400-150 mb to balance the vertical wind profile of curve (b) than that of curve (a).

Any process (either external or internal) which leads to inner cyclone upper tropospheric tangential wind increase will allow (other influences remaining constant) for surface pressure decrease in the eye and less upper level stabilization for a specified amount of tropospheric warming near the convective eye wall.

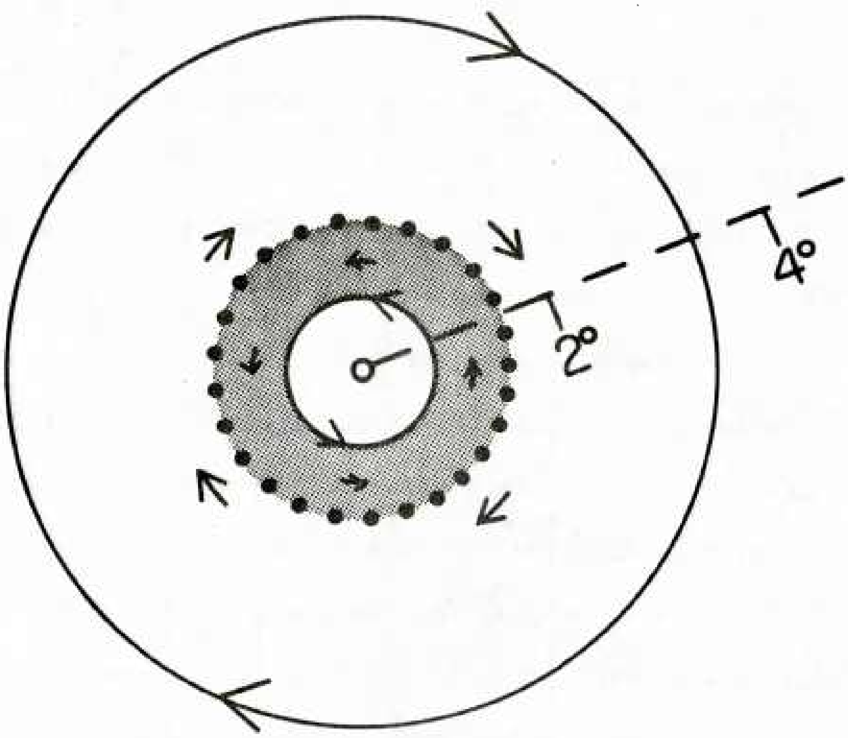

Fig. 5.6. Typical 200 mb circulation around the center of a hurricane. The shaded region shows the area of cyclonic circulation.

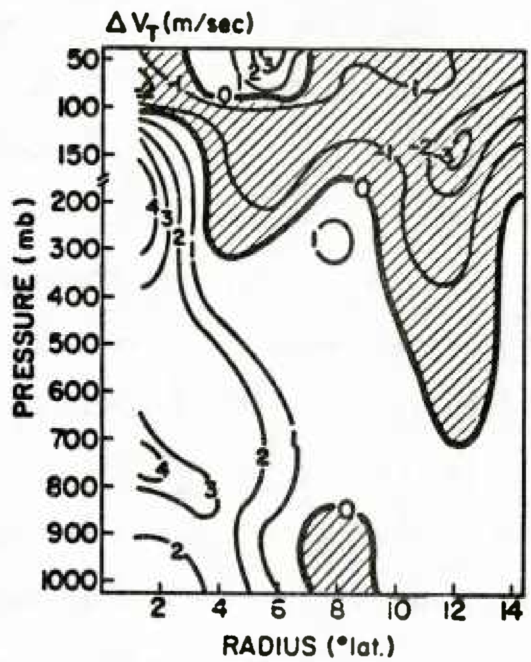

Fig. 5.7. Changes in tangential wind velocity in 24 hours for western North Pacific tropical cyclones undergoing moderate rates of intensity change of > 18 mb/24 hrs (from Edson, 1985).

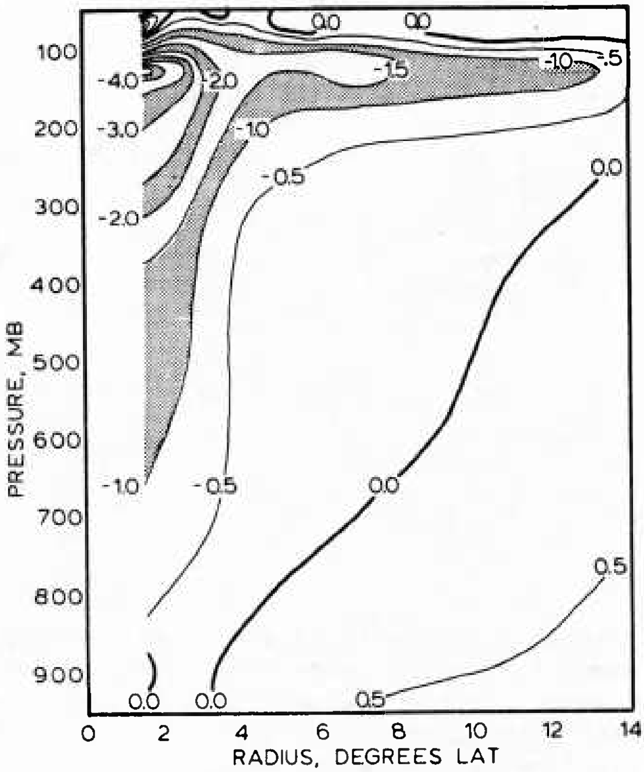

Fig. 5.8. Temperature difference (°C) between a composite intensifying typhoon and non-intensifying typhoon of similar current intensity. Negative values indicate areas where the intensifying typhoon is cooler. See text for complete description (from Merrill, 1985).

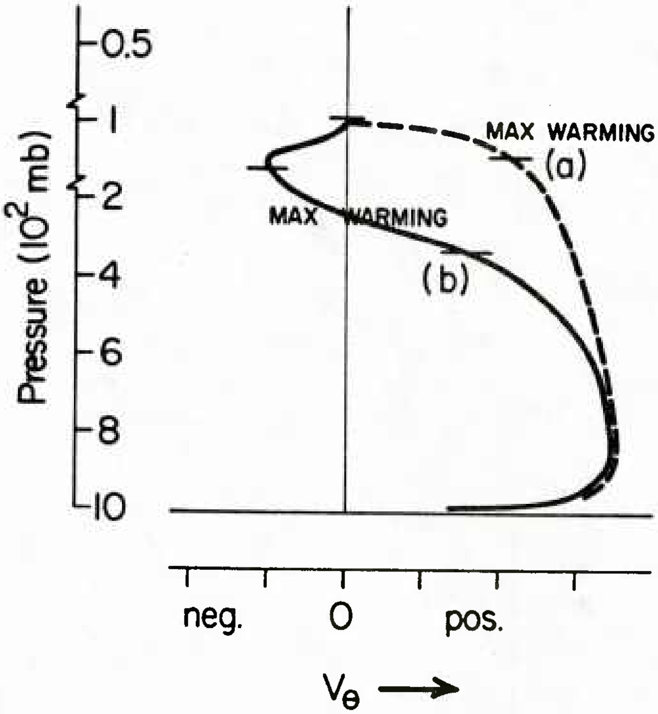

Fig. 5.9. Favorable vertical tangential wind profile near the convective cloud center of a tropical cyclone to allow maximum surface pressure drop and minimum lapse rate stability (curve a) versus a tangential wind profile which would cause less surface pressure and greater lapse rate stability in the upper tropospher (curve b).

e. Other Factors Related to Intensification

There are also other important physical processes associated with TC intensification. We observe that TC intensity change is related to at least two other primary factors:

3) Baroclinicity. Cyclones cannot intensify if there are strong vertical wind shear patterns near or over them. Vertical wind shear leads to differential advection across the tropical disturbance and a net ventilation of high energy air out of the system. Many TCs weaken or die when they are ''sheared off'' as they move into middle latitude baroclinic regions, frontal zones, etc. Many other TCs within the tropics weaken (or do not intensify) when they encounter upper-tropospheric wind patterns which are different from those of the tropical cyclone circulation itself at upper levels. These wind differences are frequently a result of baroclinicity and act as a general inhibitor on cyclone intensification. Vertical wind shear is usually a powerful inhibitor to TC intensification. The forecaster must always be on the alert for these weakening or inhibiting influences.

4) Low-level Inertial Stability. The strength of a TC's lower tropospheric outer circulation as related to its central pressure is an important factor influencing future intensity change. When a cyclone's outer radius wind circulation is stronger than average for a cyclone's particular central pressure, the cyclone's inertial stability (I^2)(2) is larger and the facility of low-level radial displacement of air parcels is reduced. This tends to inhibit mass convergence into the TC's eye-wall cloud. This inhibits cyclone intensification. Conversely, if the outer radial circulation of a TC with a particular surface pressure is weaker than average for that surface pressure, then inertical stability is less than average. The facility of radial displacement of low-level air parcels is greater. Low level convergence into the cyclone's eye-wall can more easily take place. Inner-core convection then can be enhanced more easily. Intensification is more likely (all other factors being equal).

It is typically observed that an intensifying TC crossing a particular central pressure value will have a weaker outer circulation than it does when it is at this same central pressure but is filling.

As discussed in the previous chapter, a better estimate of outer radius circulation can be made by combining information on eye-wall

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(2) $(f+2V_T/r)\zeta_a = I^2$, where f = Coriolis parameter, V_T tangential wind, r radius and ζ_a absolute vorticity.

radius and central pressure. The forecaster should observe a TC's outer circulation strength or vorticity in comparison with its central pressure and use this information to add to his qualitative assessment of a cyclone's intensification potential.

We might thus express the intensification potential of a tropical cyclone by relating the following factors:

$$\begin{pmatrix}\text{TC}\\ \text{Intensification}\\ \text{Potential}\end{pmatrix} \propto \overset{\text{A}}{\begin{pmatrix}\text{Sea-Surface}\\ \text{Temperature}\end{pmatrix}} + \overset{\underline{\text{B}}}{\begin{pmatrix}\text{Character}\\ \text{of Outflow}\\ \text{Layer}\end{pmatrix}} + \overset{\underline{\text{C}}}{\begin{pmatrix}\text{Baroclinicity -}\\ \text{A negtive factor}\end{pmatrix}} + \overset{\underline{\text{D}}}{\begin{pmatrix}\text{Low-level}\\ \text{Inertial}\\ \text{Stability}\end{pmatrix}}$$

It is recommended that the TC forecaster use each of these factors in a semi-quantitative or qualitative way to evaluate the intensity change potential of the tropical cyclone on which he/she must make a forecast.

The rest of this chapter shows examples of how processes A and B may act to facilitate the maintenance and/or acceleration of the cyclone's inner-core deep convection and thus its intensity. A discussion of the characteristics of the TC's outflow layer will now be given.

f. Outflow Characteristics Associated with TC Intensification

For many years, forecasters have often noted an association between the characteristics of a tropical cyclone's upper tropospheric outflow at radius of 5 to 10° or beyond and the cyclone's current and subsequent intensity change. Intensification is frequently observed to occur when a cyclone develops one or two concentrated upper tropospheric outflow channels on its poleward or equatorial flanks. Although a number of individual case studies have been made on this topic, there has yet to be a systematic observational study of this subject for all the world's tropical cyclone basins using identical upper level analysis procedures. The author and his research colleague (Chen and Gray, 1985) have recently discussed tropical cyclone intensity change as it is related to a storm's 200 mb environmental wind fields and satellite observed cloud patterns. All 80 tropical cyclones that occurred during the 1978-79 First GARP Global Experiment (FGGE) were studied. Use was made of the large-scale 200 mb wind analysis of the European Center for Medium Range Weather Forecasting (ECMWF) which utilizes both satellite and aircraft wind data. We will now discuss some of the basic upper tropospheric outflow differences which were found to occur with cyclone intensification within the different global storm basins.

At upper troposphere levels, almost every tropical cyclone has a corresponding anticyclone and an outward directed wind field. In most cases an anticyclone is generally found directly over or near the low-level center of the tropical cyclone and represents the location in the upper troposphere where there is a build-up of temperature from the convective activity within the center of the cyclone. This storm center anticyclone is usually embedded in or near a larger, synoptic-scale anticyclone that existed prior to the formation of the intensifying tropical cyclone. This synoptic-scale anticyclone is usually a major component of the upper equatorial or subtropical ridge in which the tropical cyclone develops. The exact location of this larger anticyclone with respect to the center of the tropical cyclone can vary a great deal. The relative location of this anticyclone with respect to the tropical cyclone center is the primary factor in determining the character of the outflow pattern and the location of the outflow channels. Figures 5.10 through 5.12 show typical 200 mb outflow patterns associated with intensifying tropical cyclones in the western North Pacific. Figure 5.10 shows a typical equatorward outflow pattern, Figure 5.11 a typical poleward outflow pattern, and Fig. 5.12 a double outflow channel pattern. Figure 5.13 gives a summary of the variety of outflow patterns which can occur with tropical cyclone intensification as a result of the relative positioning of the surrounding synoptic-scale upper level anticyclones.

There are three basic types of upper tropospheric surrounding environmental wind which lead to the establishment or intensification of cyclone outflow channels:

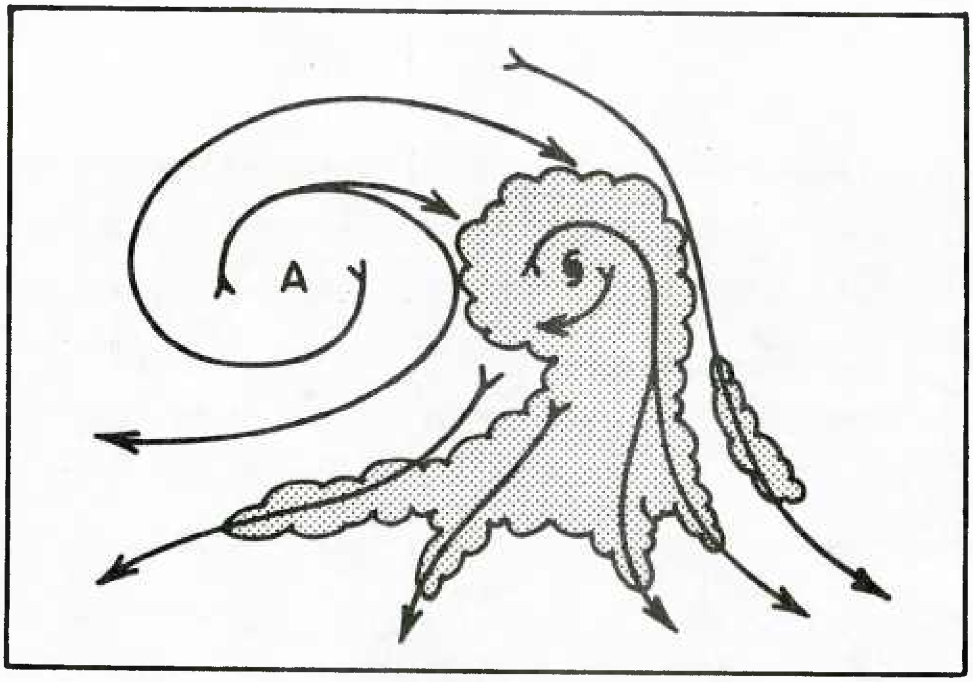
i) Opposite hemisphere influences,

ii) Middle latitude upper trough and/or westerly wind influence on the poleward side of the cyclone such as a Tropical Upper Tropospheric Trough (TUTT), and

iii) A combination of process (i) and (ii).

i) <u>Opposite-hemispheric influences</u>.

A strong equatorial upper level anticyclone in the Southern Hemisphere (S.H.) is extremely favorable for enhancing the equatorward



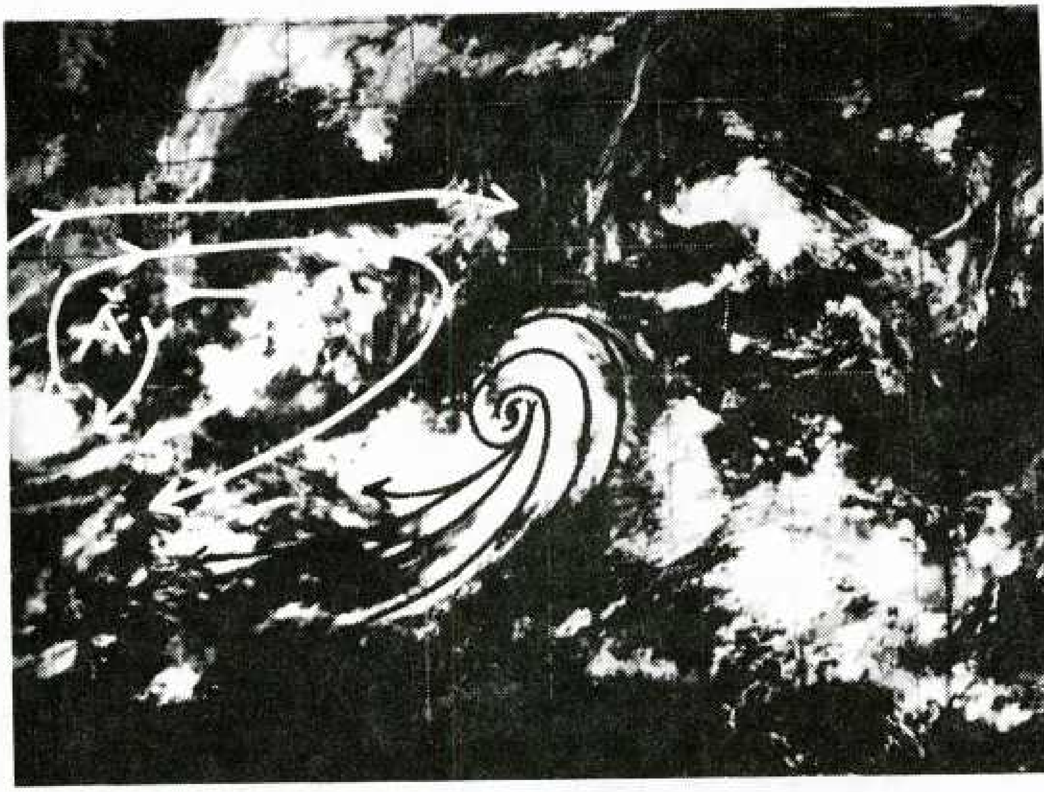
(a)

200 mb

(b)

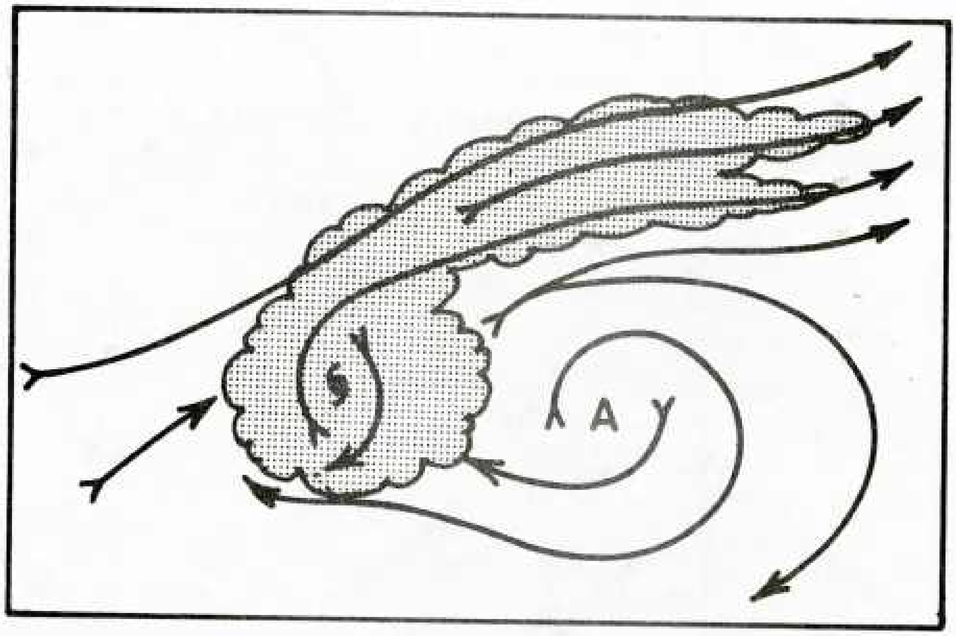
13 AUGUST 00Z

Fig. 5.10a-c. Pattern S_{Ee}: Diagram (a) a single equatorward channel for a cyclone center to the east of the anticyclone center. Diagram (b) 200 mb flow for Typhoon Irving on 13 August 1979. Diagram (c) 0611 GMT 12 August 1979 DMSP display (Typhoon Irving). From 12 to 15 August the maximum sustained winds increased from 50 to 90 knots.



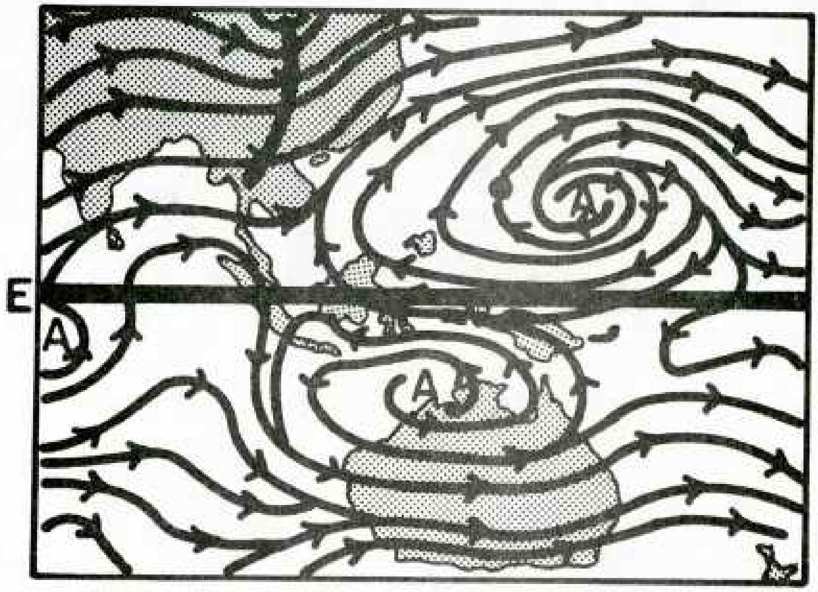
(c)

Fig. 5.10c. Continued.



(a)

200 mb



(b)

22 MARCH 00Z

Fig. 5.11a-c. Pattern S_{P_W}: Diagram (a) is an idealized picture of a single poleward 200 mb outflow channel with the cyclone center to the west of the 200 mb anticyclone center. Diagram (b) 200 mb winds on 22 March 1979 for future Typhoon Bess. Diagram (c) 1600Z 22 March 1979 DMSP display (Typhoon Bess). From 22 to 24 March the maximum sustained wind increased from 55 to 90 kts.

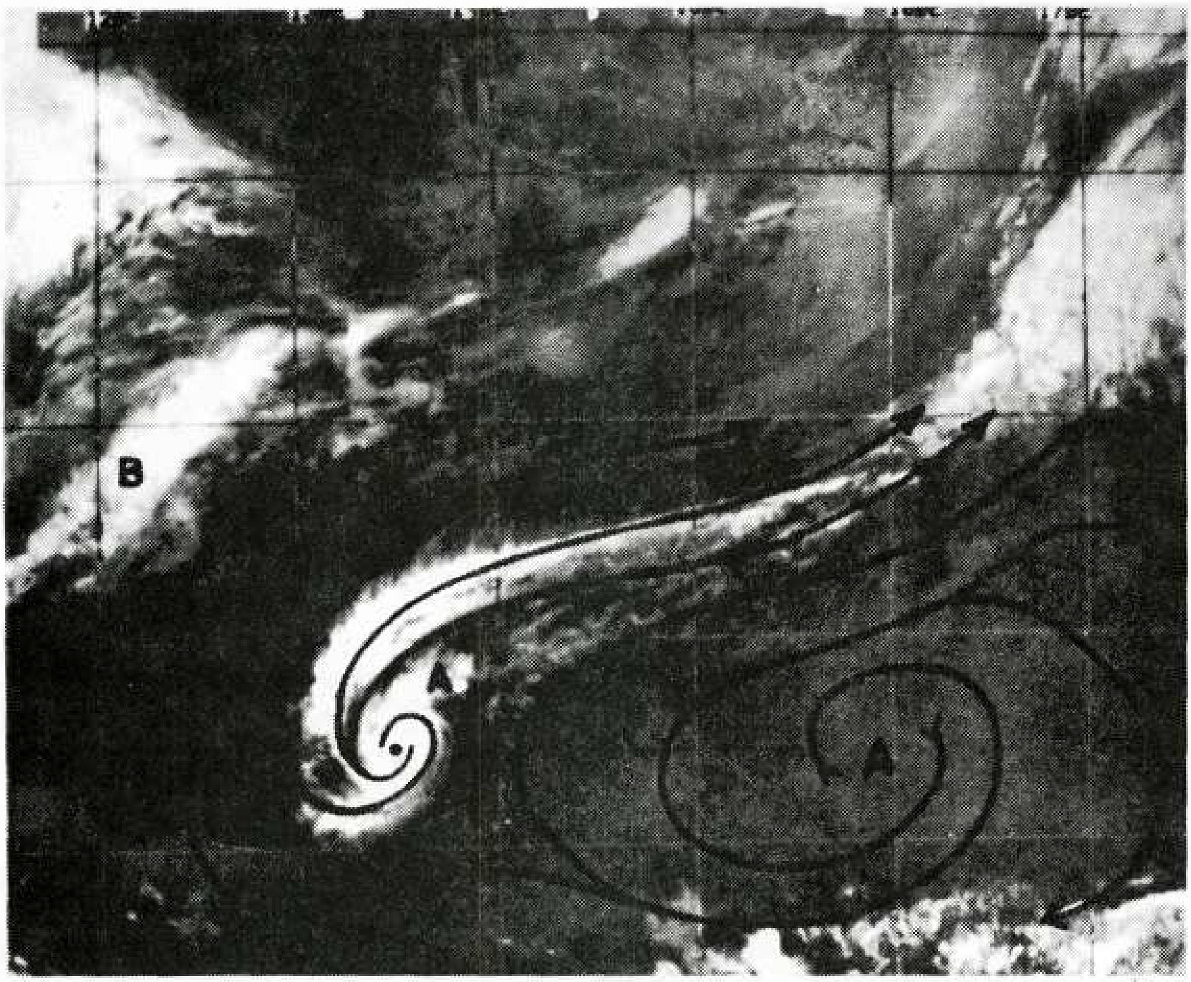
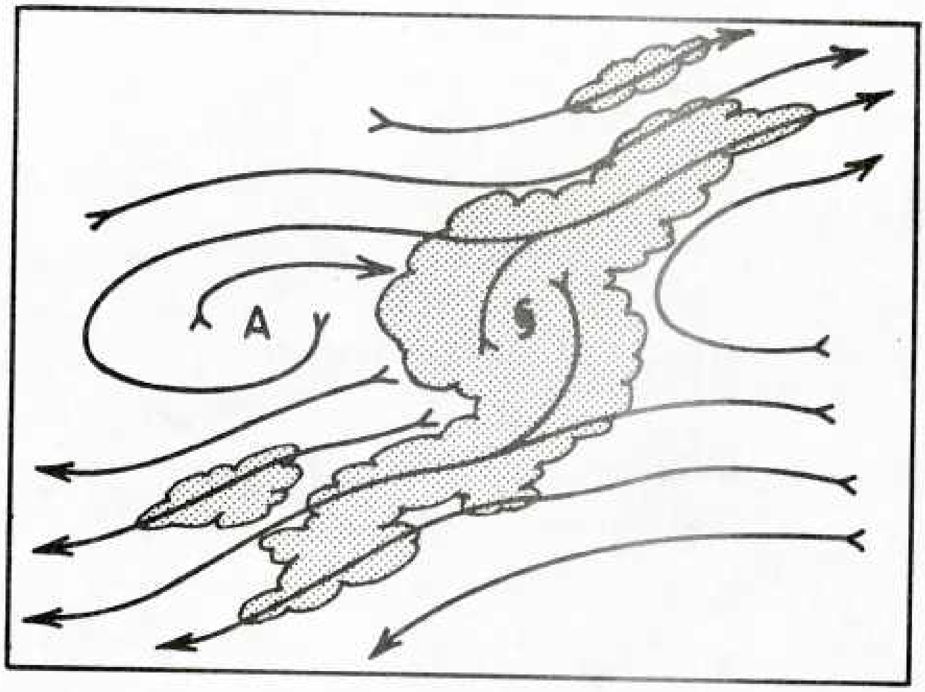
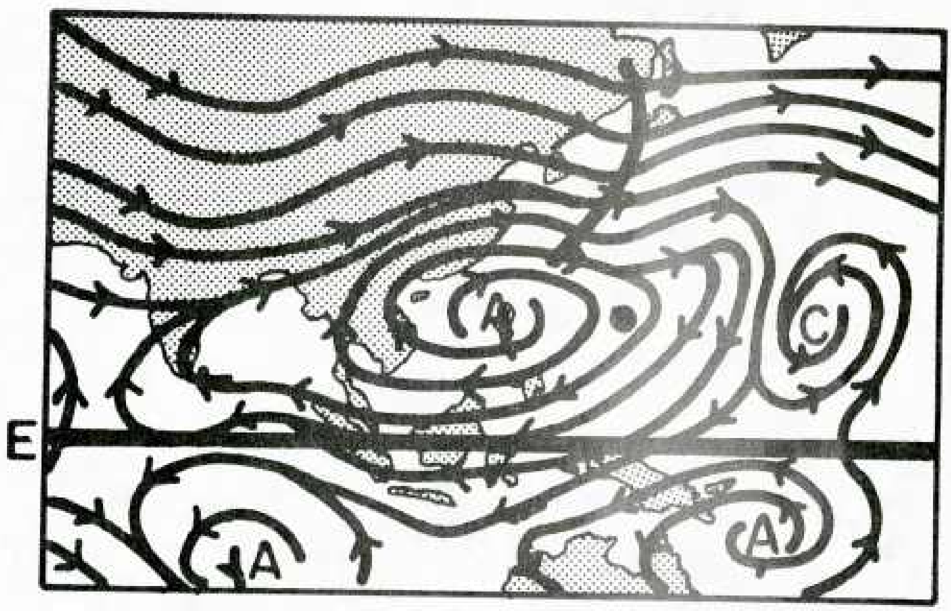


Fig. 5.11c. Continued.



(a)

200 mb



(b)

12 OCTOBER 00Z

Fig. 5.12a-c. Pattern D_e: Typical case of a double channel outflow with the cyclone center east of the anticyclone center, Diagram (a). Diagram (b), 200 mb 12 October 1979 for Typhoon Tip. Diagram (c) 1601 GMT 12 October 1979 DMSP display Typhoon Tip. From 10 to 12 October the maximum winds increased from 80 to 165 knots.

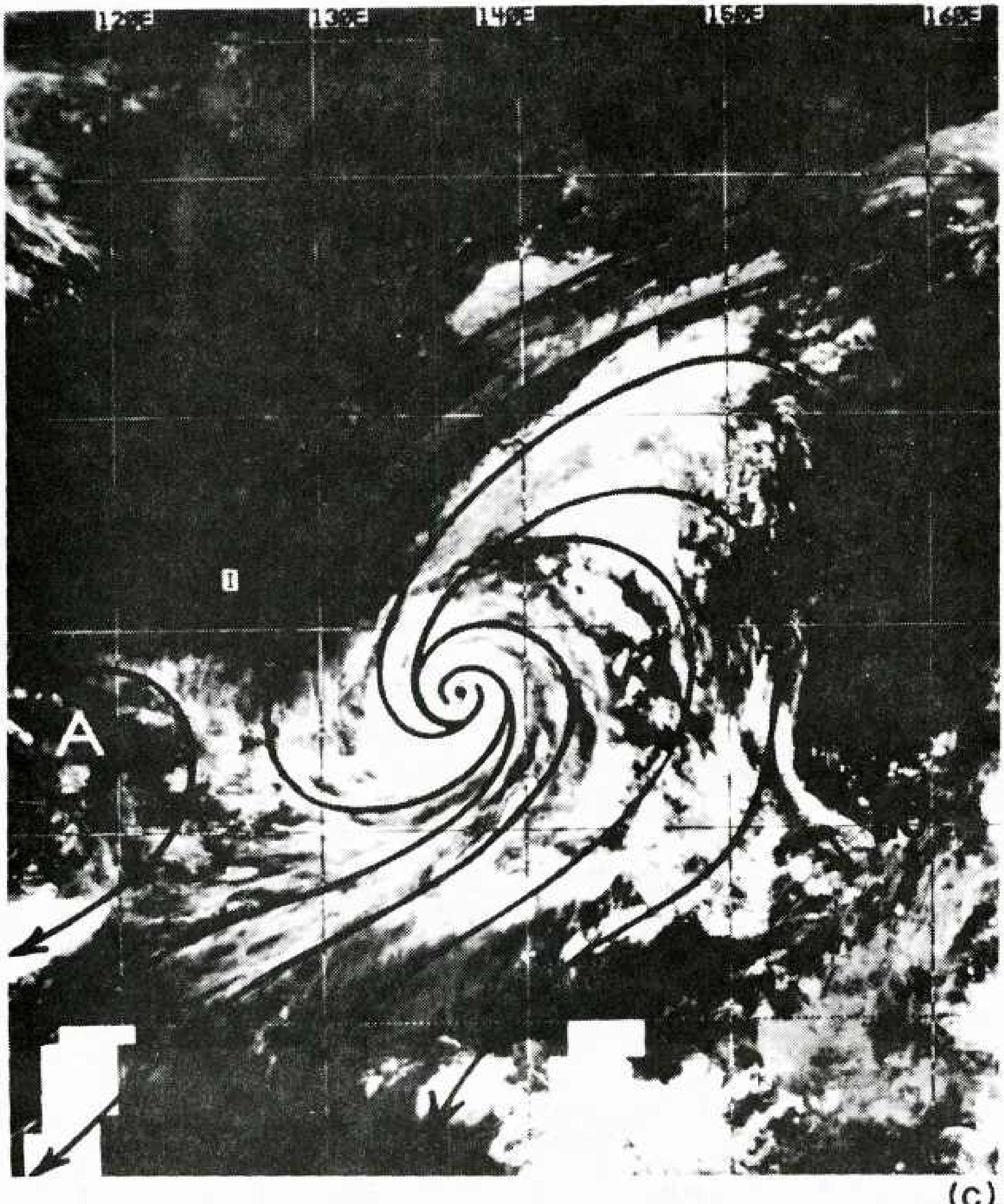


Fig. 5.12c. Continued.

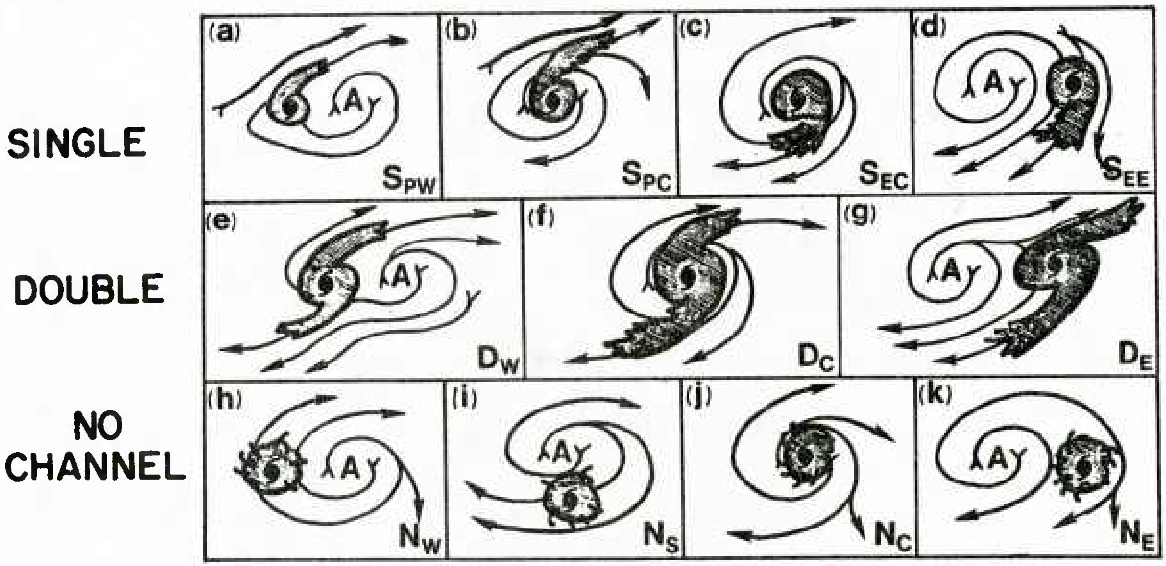


Fig. 5.13. Variety of outflow patterns associated with tropical cyclone intensification for Northern Hemisphere cases (Chen and Gray, 1985).

outflow of a Northern Hemisphere (N.H.) tropical cyclone and vice versa. In particular, when a low latitude anticyclone of the opposite hemisphere increases its strength or builds from east to west into a position just equatorward of the tropical cyclone, a general strengthening of the equatorial outflow channel of the tropical cyclone is frequently observed. This often leads to an intensification of the cyclone.

ii) Middle latitude Influence

When a mid-latitude long-wave trough, moving eastward, approaches close enough to a tropical cyclone, conditions became favorable for the establishment or the strengthening of a poleward outflow channel. Similarly, a tropical cyclone may approach an upper level TUTT and have its outflow enhanced.

iii) Combined influence

When a mid-latitude long-wave trough and an equatorial upper level anticyclone of the opposite hemisphere approach to the north or south of a tropical cyclone from different directions, strong double outflow channels (D pattern) can be developed. Such an interaction can frequently have a powerful influence on very rapid tropical cyclone development and intensification.

Model Synthesis of Various Types of Interaction. Chen and Gray (1985) have isolated six basic types of cyclone and environment 200 mb wind field interaction which occurred during the FGGE year. These are shown in Fig. 5.14 and described below:

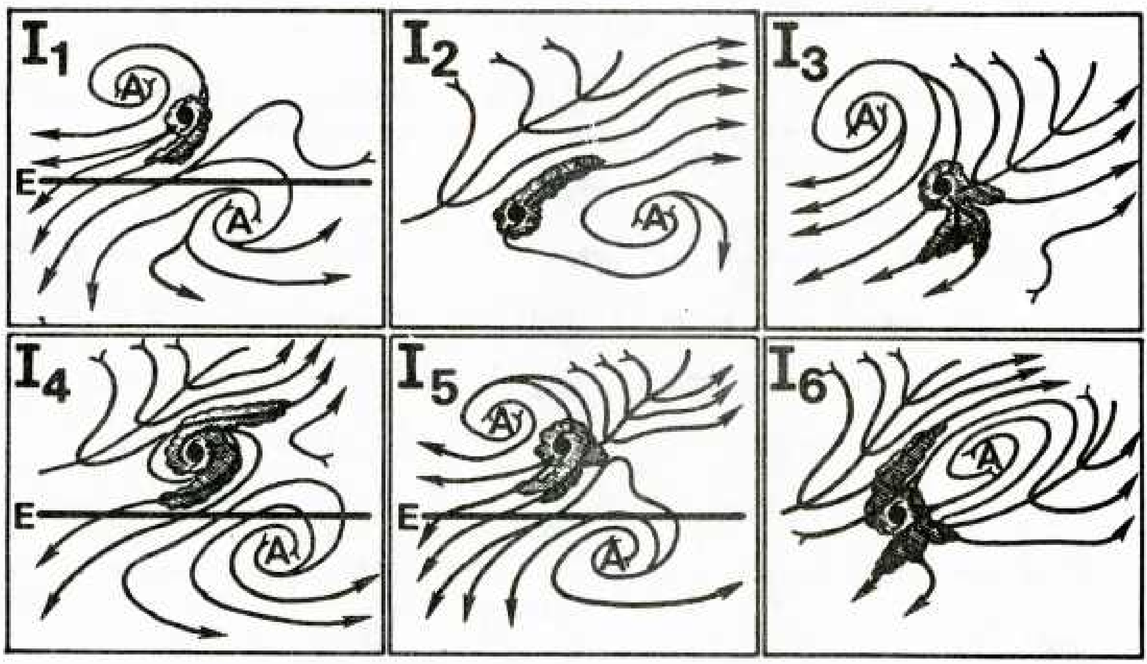


Fig. 5.14. Six types of interactions between a tropical cyclone and its surrounding.

I_1 Equatorial anticyclone of the opposite hemisphere enhances a single equatorward outflow channel (S_e).

I_2 Long-wave middle latitude trough moving eastward to the poleward and west side of the cyclone enhances a single poleward outflow channel (S_p).

I_3 Tropical cyclone located at the tip of, or just to the rear of, a long-wave trough or TUTT, enhancing a single equatorward outflow channel (S_e).

I_4 Mid-latitude long-wave trough or TUTT and equatorial anticyclone of the opposite hemisphere approach a tropical cyclone from different directions and establish double outflow channels (D) in both poleward and equatorward directions.

I_5 Combined effect of an equatorial anticyclone of the opposite hemisphere and the tip of a transverse shear line over the mid-ocean enhance a single equatorial outflow channel (S_e).

I_6 Tropical cyclone flanked by western and eastern shear lines, establishing double outflow channels (D).

Some of these interaction patterns are more prevalent than others. Table 5.1 gives a tabulation of the frequency of these various interaction models by class for the FGGE year. Eighty-nine percent of the systems with poleward outflow channels (S_p pattern) were associated with the approach of a mid-latitude long-wave trough or a Tropical Upper Tropospheric Trough (TUTT). Eighty-four percent of equatorward outflow channels are associated with favorable positioning of low latitude anticyclones of the other hemisphere. Thirty-four percent of equatorial outflows not associated with an opposite hemisphere anticyclone are the

TABLE 5.1

Frequency of interaction types in different outflow patterns during the FGGE year. X means that no interacting outflow cloud channels were detected with this flow configuration. N means that none of these three basic outflow wind features were present.

Patterns	S_P		S_E				D		N		
Interaction Type	I_2	X	I_1	I_5	I_3	X	I_4	I_6	X	I_1	
Number	25	3	18	9	2	3	5	1	9	5	
Total	28		32				6		14		Total 80

result of tip or rear effects of a 200 mb trough or TUTT shear line. Double channels occur with the lowest frequency (less than 10 percent). Outflow channels of some sort are usually observed with cyclone intensification. Sadler (1978) has frequently emphasized this point. Of the 80 FGGE-year tropical cyclones that underwent intensification or development, 59 or 74% were observed to possess some type of distinct 200 mb outflow channel or channels.

The frequency of occurrence of these upper-level cyclone-environment interaction patterns varies according to region and time of year. In mid-summer, intensification in the North Pacific is frequently associated with the effect of an anticyclone of the opposite hemisphere. On the other hand, the influence of a mid-latitude long-wave trough to the northwest of the cyclone (excluding tip and rear effects of shear line TUTT troughs over the mid-ocean), is primarily a feature of the autumn, winter, or spring. All tip or rear of trough effects of a transverse shear line over the mid-ocean (models I_3, I_5, and I_6) occurred in the summer — especially over the northwestern Pacific.

These outflow models also vary in frequency for the different ocean basins. The ocean basins most influenced by equatorial anticyclones of the opposite hemisphere are the northeastern Pacific (92%) and the northwestern Pacific (52%) basins. This is opposite to the situation in the S.H. Only 9% of S.H. FGGE-year tropical cyclones were influenced by an equatorial anticyclone of the northern hemisphere. Most of the FGGE-year tropical cyclones which intensified in the S.H. (82% in the South Indian Ocean, and 63% in the Southern Pacific) were associated with a mid-latitude long-wave trough to their west (I_2 pattern that is inverted).

Poleward outflow patterns are also prevalent for tropical cyclones over the North Indian Ocean. These cyclones occur only in late spring and autumn. This is the time when middle latitude westerly waves are just able to pass to the south of the Tibetan plateu and draw in poleward directed outflow from the tropical cyclone.

Over the central Atlantic in summer, a quasi-stationary transverse shear line or TUTT typically exists. Tropical cyclones which intensified over the North Indian Ocean (only in spring or autumn) or the North Atlantic are thus mostly associated with the effects of middle latitude troughs and/or upper level shear lines (67%).

Tables 5.2 and 5.3 summarize the regional variability of outflow patterns. For N.H. cyclones, equatorward outflow channels occur twice as frequently as poleward outflow channels. This situation is reversed in the S.H. where poleward outflow channels are three times as frequent as equatorward outflow channels. Global statistics show that poleward outflow channels and equatorward outflow channels occur with about the same frequency.

TABLE 5.2

Outflow patterns of the different tropical cyclone basins of the Northern Hemisphere during the FGGE year with the percentages of each outflow pattern in parentheses.

Outflow Patterns	S_P	S_E	D	N	Total
NW Pacific	5(16)	16(52)	2(7)	8(26)	31(100)
N. Indian Ocean	4(67)	2(33)			6(100)
NW Atlantic	2(22)	1(11)	4(45)	2(22)	9(100)
NE Pacific	1(8)	8(67)		3(25)	12(100)
Northern Hemisphere Total	12(21)	27(47)	6(10)	13(22)	58(100)

TABLE 5.3

Same as Table 3 but for the Southern Hemisphere.

Outflow Patterns	S_P	S_E	D	N	Total
SW Pacific	7(64)	4(36)			11(100)
S. Indian Ocean	9(82)	1(9)		1(9)	11(100)
Southern Hemisphere Total	16(73)	5(23)		1(5)	22(100)

It is important that forecasters recognize and appreciate the geographic and seasonal differences in outflow patterns associated with tropical cyclone intensification.

g. Environmental Linkages to the Inner Core

What physical processes are responsible for the apparent association of outflow channel concentration and inner storm intensification? The observations of our project indicate that when a tropical cyclone's outer radius (~5-15°) 200 mb outflow is concentrated in narrow and strong channels (as opposed to broader and more uniform and weaker outflow channels) that conditions for inner cyclone concentration of deep-convection are more favorable. When the tropical cyclone's upper level outflow is not concentrated in strong and narrow outflow channels, however, then the conditions necessary to concentrate inner-core deep convection are, in general, much less favorable. Thus, the 200 mb mass outflow configuration as shown in the left diagram of Fig. 5.15 is more conducive to cyclone intensification than the outflow configuration of the right diagram.

The observations and hypothesis of Merrill (1985) and the observational results discussed in this paper imply that tropical cyclones with strong outflow channels likely have a greater upper level eddy import of tangential momentum to the region of central convection than do tropical cyclones without such concentrated outflow channels. The physical link between tropical cyclone eye-wall convection enhancement and outflow channels is thus believed to take place through

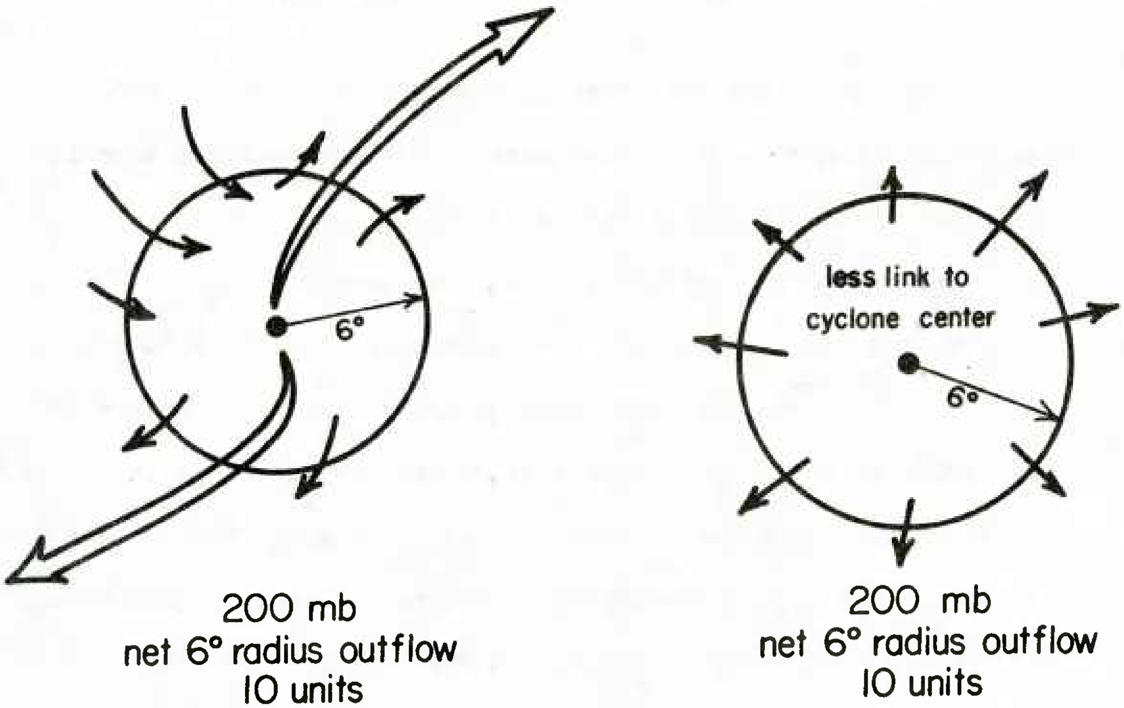


Fig. 5.15. Contrast of 200 mb cyclone outflow patterns with concentrated channels (left diagram) vs. a cyclone with uniform outflow and no concentrated outflow channels.

the association of such outflow channels with enhanced inward upper-level tangential eddy momentum flux to the cyclone's central region of maximum convection.

When outflow is concentrated in strong anticyclonically curved outflow channels as shown by the left diagram in Fig. 5.15, mass requirements dictate that there also be a degree of compensating inflow. This upper level inflow may move towards the center with tangential momentum larger than the outflowing air at the same radius. This results in an inward eddy momentum flux which would not be possible were the outflow more nearly symmetric, as shown by the right diagram of Fig. 5.15.

This is an overly simplified view. The actual dynamics of this inward eddy momentum flux appear to be very complicated. Merrill (1985) has presented evidence and has hypothesized that this needed upper level inward momentum flux may occur due to standing wave (Wave No. 1 or 2) momentum fluxes. These waves are developed through upper level barotropic instability processes at radii between about 2-5° or so. When such an intermediate radius barotropic wave becomes azimuthally superimposed upon an environmental wave or special flow pattern on the tropical cyclone's flank at radius of 10-15°, an important outer to inner core upper level momentum transport may result. The reader should refer to Merrill's study for a more detailed discussion of this hypothesis. Although Merrill's intensification ideas have been developed for hurricanes undergoing intensification change in the Atlantic basin, it is believed that the general physical processes - as he has advanced them - likely apply in a similar fashion in the other tropical cyclone basins. The hypothesized physical linkages might be summarized in the following flow diagram of Fig. 5.16.

These upper tropospheric linkages between the tropical cyclone and its environment need much more research. Although not well understood, the majority of the experienced tropical cyclone forecasters indicate that some type of upper tropospheric linkages are typically present with cyclone intensification.

h. Summary Discussion

The prediction of tropical cyclone intensity change remains a complicated subject. While many associations of 200 mb outflow with tropical cyclone intensity change have been demonstrated here, other factors such as sea-surface temperature (SST), lower tropospheric outer radius wind strength, background climatology, etc., can also influence a tropical cyclone's potential for intensity change. Sometimes tropical cyclone intensity change will not occur despite the presence of highly favorable outflow conditions. Other times when outflow conditions are only marginally satisfactory, a tropical cyclone may intensify anyway because other factors are very favorable. Nevertheless, the outflow channel and intensity change relationships discussed in this paper appear to be associated with a substantial fraction of the intensity change which typically occurs. Outflow characteristics should be utilized as much as possible when making intensity change predictions.

It is hoped that the general discussion of this chapter will give the TC forecaster a little better background for understanding and appreciating the complexities of the TC intensification process and that, from this background knowledge, he/she may be able to improve his/her forecasting of this process.

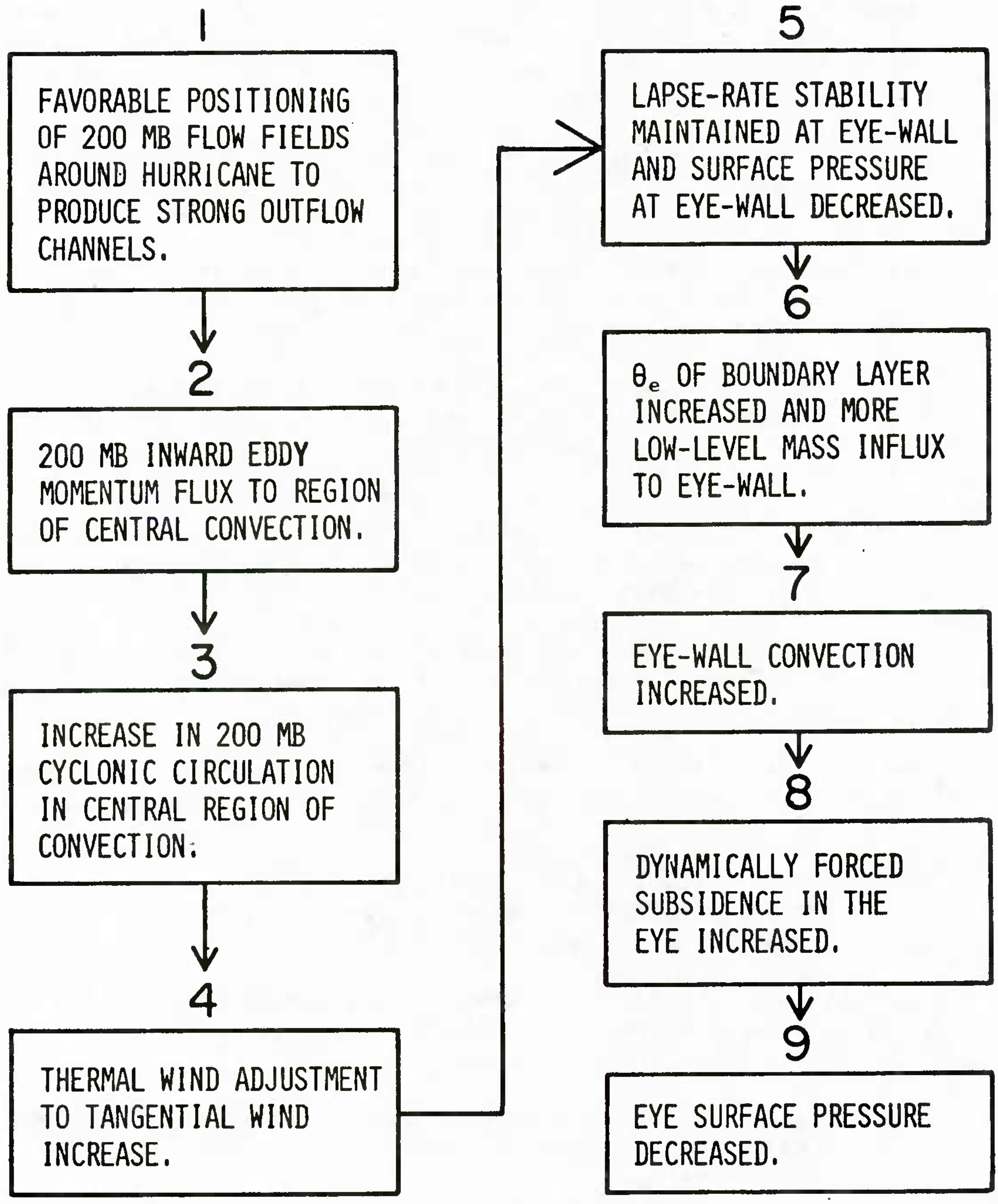


Fig. 5.16. Idealized view of how favorable environmental conditions at 200 mb might lead to an increase in tropical cyclone inner-core intensity change.

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6. Tropical Cyclone Outer-wind Speed as Related to Satellite IR Cloud Shield Width

a. Background Discussion

The radial extent of strong tangential winds around a typhoon is often difficult to quantitatively assess. As previously discussed, some typhoons have very intense central core wind velocities but only weak outer circulations. Other typhoons of only moderate minimum pressure have very strong outer circulations. Other factors besides central pressure or maximum wind must be used to estimate a tropical cyclone's outer circulation.

Through analyses of three years of northwest Pacific standardized aircraft reconnaissance radial leg fight tracks (as discussed in Chapter 4), Weatherford (1985) has recently documented the large variety of outer wind circulations for tropical cyclones of similar central pressure and maximum wind velocity. At the present time there are no established procedures whereby a typhoon's outer circulation can be objectively estimated over data-sparse regions where only satellite data are available. It is important that procedures be developed for these situations.

Wei and Gray (1986) have recently made comparisons of ten years of rawinsonde composites of northwest Pacific typhoons of large vs. small area extent of satellite-observed cloudiness. Although each of these two composites had nearly identical average central pressure and maximum wind velocity, the outer wind strength, net rainfall, and kinetic energy inside 10° radius of the typhoons of large area extent of cloudiness were considerably more (by factors of 2-3) than the typhoons of small area extent of cloudiness.

This and other studies indicate that we should not be surprised by the now over a quarter-century of satellite observations which have shown that the size of a tropical cyclone's cloud shield is not well correlated with its central pressure or maximum wind velocity. Dvorak's (1975, 1984) method for estimation of tropical cyclone inner-core intensity from satellite data relies primarily on the cyclone's cloud banding features and their curvature; little or no consideration is given to the total area extent of cloud coverage. This observation has been well borne out in research on our project by Arnold (1977) who showed that the amount of deep convection and cloudiness within northwest Pacific tropical cyclones has very little relation to the cyclone's minimum central pressure or maximum winds.

Outer wind circulation differences appear to be a consequence of the different environments in which the typhoon forms or the environment into which it moves. But regardless of cause it may be possible that a typhoon's area extent of cloudiness could be utilized in some way as an indicator of the cyclone's outer radius wind strength.

Weatherford (see Fig. 6.1) has documented the large statistical range of typhoon and tropical cyclones' outer wind strength values (1-2 $1/2^{\circ}$ radius mean tangential wind) and how variable and little correlated are a typhoon's mean radius of 30 and 50 knot surface winds with its central pressure (see Figs. 4.4 and 4.5 from Chapter 4).

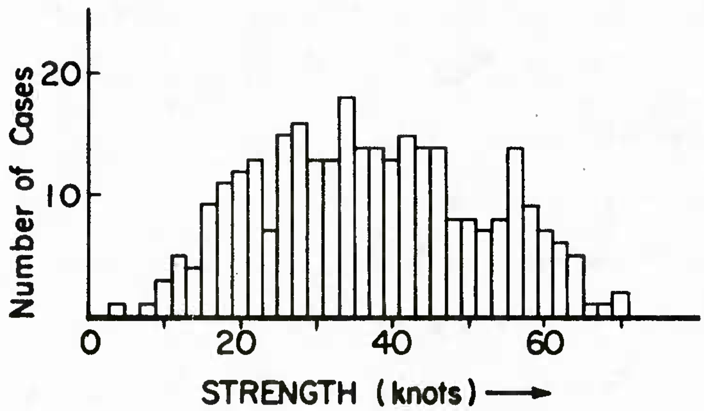

Fig. 6.1. Histogram of 1-2 1/2° radius mean tangential wind or strength for all 1980-82 reconnaissance flights into cyclones of typhoon or tropical storm intensity. (From Weatherford, 1985).

b. Scope of This Anomaly

Wei and the author (Wei and Gray, 1986) have recently made a study to determine if some relationships can be established between a tropical cyclone's outer circulation and some other cyclone parameter (besides central pressure of maximum wind) such as the TC's area extent of satellite observed cloud shield. Analysis is made for the 3-year period of 1980-82 when all Guam based typhoon aircraft reconnaissance data were available in conjunction with 3-hourly Japan Synchronous Meteorological Satellite (SMS) IR satellite images. This study attempts to determine if there is any useful relationship between the strength of the cyclone's outer circulation and the area extent of its satellite-observed cloud shield.

It is found that the areal extent of the tropical cyclone's cloud shield and magnitude of its outer circulation do indeed have a statistical relationship. This relationship is used to propose an objective and quantitative method for estimating the tropical cyclone's outer circulation when aircraft and convection observations are not available but satellite IR images are. When aircraft and conventional data are available, this method might be used in a complementary or supplementary sense.

c. Analysis Procedures

Wind analysis was performed along the four standardized 700 mb flight legs which are flown on nearly all flight missions (see Fig. 4.2). The radial extent of the 700 mb 35-knot isotach was noted on each radial leg flight. The four radial legs were then averaged to give a mean radial extent of 35-knot winds. It was assumed that the surface (or 10 meter height) wind speeds over the open ocean are about one-seventh less than the 700 mb level speeds or that 35-knot winds at 700 mb are approximately equivalent to 30-knot winds at the surface. Also that the radius of 60-knot flight level winds are approximately equivalent to the radius of 50-knot surface winds. All flights were tabulated in an identical manner.

Once this four radial leg wind information was obtained for each flight mission, it was compared with the mean area extent of the Japan SMS satellite observed IR cloud shields at the closest picture time. As IR satellite information was available every 3 hours, flight and satellite data were always within a few hours of each other.

Flight missions were typically flown twice a day to obtain center fixes around the hours of 00Z (~ 9-10 Local Time) and 12Z (~ 21-22 Local Time). Most flight legs were flown between the local hours of about 06 to 12 and 18 to 24. A statistical analysis of the cloud shields showed no diurnal bias in the area extent of cloudiness between these two times.

d. How Cloud Shield Determinations are Made

Figures 6.2 through 6.5 portray information on how the mean radius of the satellite-observed cloud shields were determined. Although considerable ambiguity can be present in many of these measurements, one can, on average, obtain a reasonable estimate of the mean diameter of the typhoon's central cloud shield from the Japan SMS satellite IR pictures. It is important that one not include the outer rainbands in the area average, however, and that one only use IR pictures. A comparable relationship might also be obtained with satellite visual pictures, but the relationship here discussed was accomplished only with IR pictures. IR pictures can frequently detect cirrus clouds which are often not seen in visual pictures. One should use only the area extent of the cyclone's overcast cloud shield.

Clouds need not be symmetrical, but the environmental boundary line of the satellite picture must be clear enough to be easily distinguished. This is an important point. For measuring the mean radius $\bar{r}$ of the storm cloudiness one must first select the long axis $\overline{AB}$ and then a short axis $\overline{CD}$ and measure them in degrees latitude as shown in Fig. 6.2. The mean radial extent of cloudiness ($\bar{r}$) in degrees latitude would then be given by:

$$\bar{r} = \frac{\overline{AB} + \overline{CD}}{2} \qquad (1)$$

If there are wide cloud bands which are slightly split away from the main cloudiness, they should be included even though some small clear regions may be seen within the whole cloud area. The cloud clear boundary line should be well-defined as shown in Fig. 6.3.

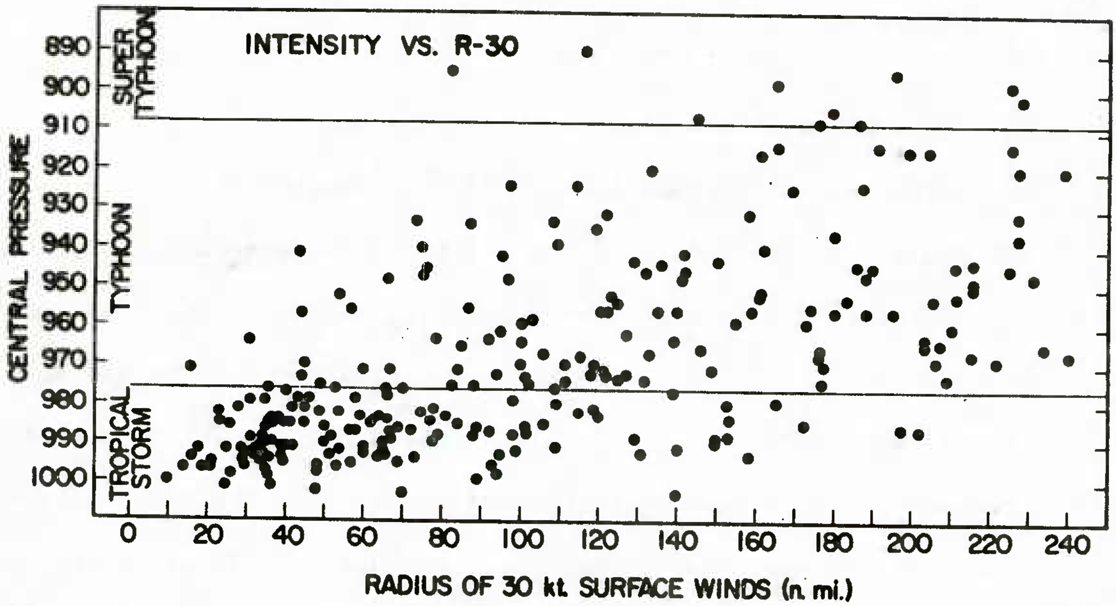

Fig. 6.2. Measuring the mean size of the cloudiness with nearly round and ellipse forms.

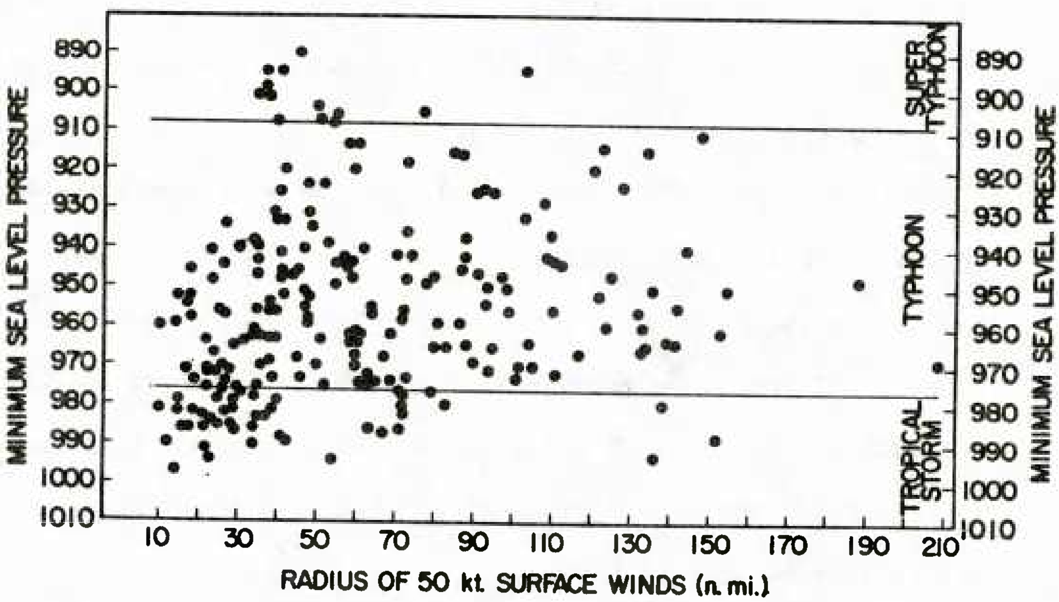

Fig. 6.3. The measurements of the mean size of the cloudiness with wide cloud bands spinning in.

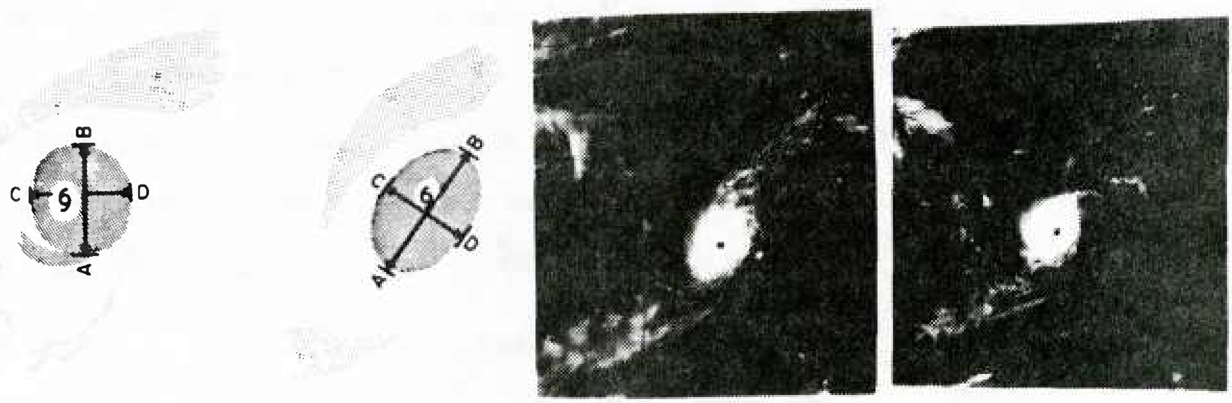

Fig. 6.4. The measurements of the mean size of the cloudiness with long and thin cloud bands spinning in, etc.

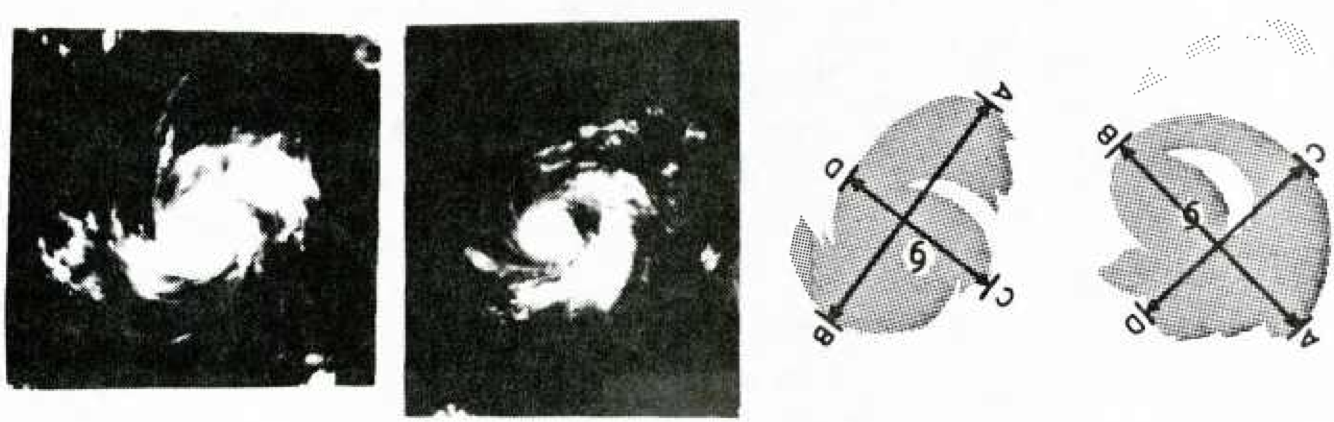

Fig. 6.5. The measurements of the mean size of the cloudiness with some very light cirrus.

If there are thin and long cloud bands eminating into the main cloudiness shield as seen in Fig. 6.4, they should not be included in the cloud shield width determination.

If there are some very light cirrus clouds which join to, but are just outside, the main cloud area of the tropical storm, they should also not be included. In this case the main cloudiness-clear boundary line is still well-defined, as shown in Fig. 6.5. $\overline{AB}$ and $\overline{CD}$ should be determined as indicated in the idealized diagrams which accompany these four figures.

e. Cloud Shield and Outer Wind Relationship

Figure 6.6 shows a plot of 700 mb mean 35-knot wind radius vs. mean radial extent of IR cloud shield. Note that although a sizable scatter is involved with this data, there is a general relationship between the cyclone's average radius of cloud shield and the average radial extent of 700 mb 35-knot wind speeds. This is to be expected. The larger the cyclone's outer wind circulation, the larger the cyclone's mass inflow, evaporation, rainfall, and generally greater area extent of cloudiness. It is suggested that this relationship be used when other supporting observations are not available.

The relationship of Fig. 6.6 can be quantitatively expressed as:

$$\bar{r}_{wind} = 1/2(\bar{r}_c - 40) \text{ where}$$

$\bar{r}_{wind}$ = mean radius of 30-knot surface wind expressed in nautical miles (n mi)

$\bar{r}_c$ = mean radius of IR observed cloud shield in nautical miles (n mi).

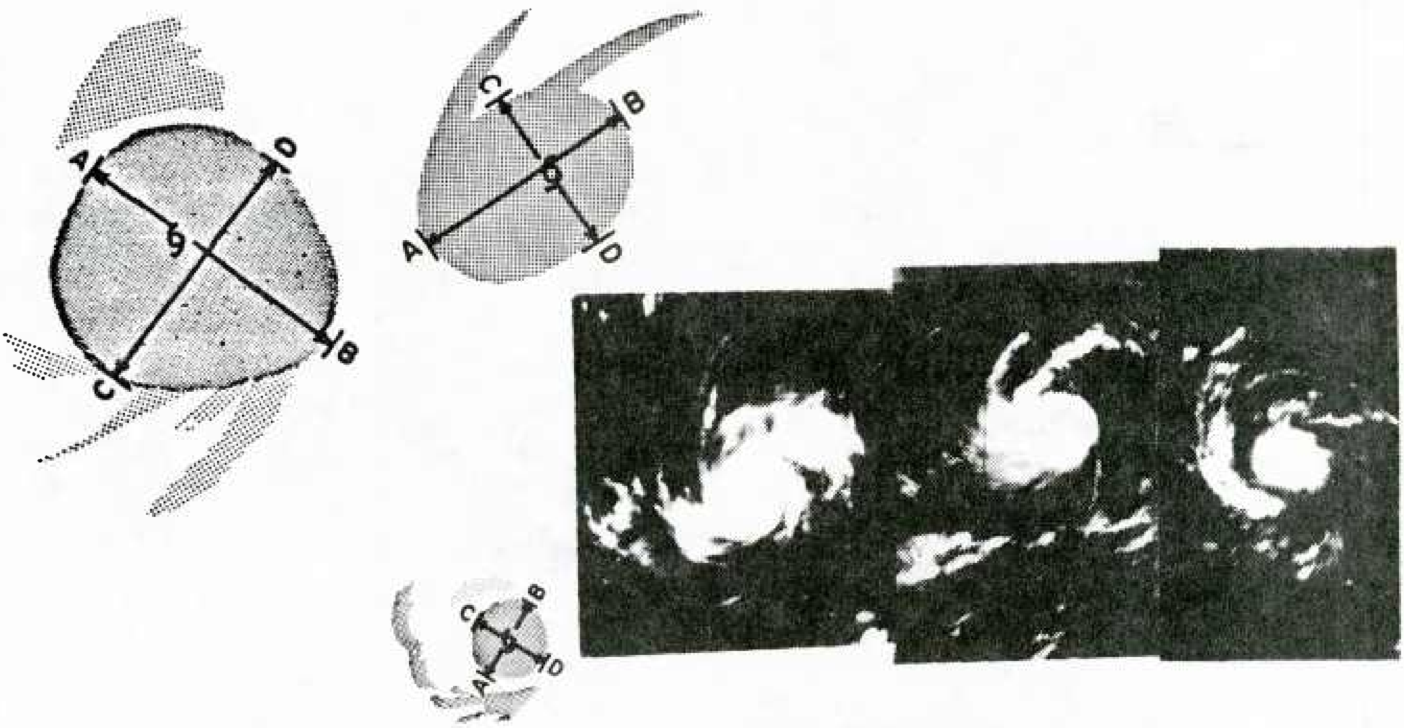

Fig. 6.6. Relationship between the mean radius of 700 mb 35 kt and the mean radius of satellite observed cloudiness.

This relationship was developed with aircraft reconnaissance data which, however, did not extend beyond 150 to 240 n mi (2 1/2 - 4°). This relationship could not be verified for those typhoons with large outer radial circulations, and must be extrapolated for those typhoons. The extent to which this relationship may be altered by such an extrapolation is not known.

In contrast with the previous discussions in this paper, one should not expect to observe the area of the typhoon's cloud shield to show much relation to the estimated maximum wind speed of the typhoon. This holds true. Figure 6.7 shows that the cyclone's maximum wind speed

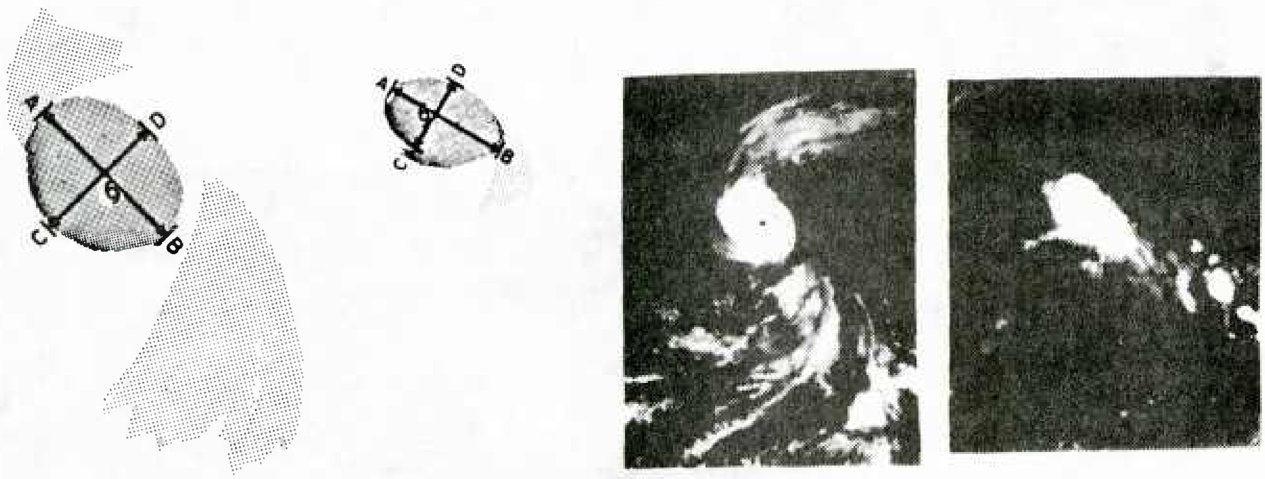

Fig. 6.7. Relationship between the tropical cyclone's estimated maximum wind and the mean radius of satellite observed cloudiness.

does not possess a notable correlation with the cyclone's area extent of cloudiness.

The most difficult part of this procedure is to obtain a reasonable estimate of the radial extent of satellite observed cloudiness. This can, at times, be difficult and some ambiguity can occur. Nevertheless, this is an important measurement and an important conceptual view to have.

f. Summary Discussion

This chapter has been written to focus more attention on the subject of typhoon outer radius wind strength variability and to show that there may be a way to utilize satellite cloud imagery to obtain an estimate of a typhoon's outer wind strength when other estimates are not available. Some forecasters may already be using outer cloudiness as a measure of cyclone outer circulation in a qualitative manner. This type of relationship could not have been developed without utilization of the Guam reconnaissance information. Atlantic aircraft reconnaissance does not have near the radial range which the Guam flights do.

The general cloud-outer wind relationship shown here should have been qualitatively expected. A cyclone with stronger than average outer radius wind speeds will have more outer radius evaporation and a higher outer radius vorticity field with larger associated boundary layer frictional convergence. This should be associated with more outer radius convection and cloudiness.

This cloud-wind relationship was developed for typhoons of small-to-moderate outer area circulation. In a number of the larger circulation typhoons, aircraft reconnaissance data did not extend to a large enough radius such that a cloudiness 30-knot wind radius relationship could be measured. It is felt that this relationship should, in a general sense however, also be valid for those typhoons with especially large outer circulations.

The reliability of this relationship within individual quadrants of the large outer circulation typhoons should also be expected to be generally less valid. Environmental wind influences are more pronounced at outer radii. As conventional observational information is usually more available to measure the 30-knot wind radius of the large outer circulation typhoons than that of the smaller cyclones, this relationship will likely be more useful for typhoons of average or small radial extent of cloudiness.

This outer wind and cloud shield relationship was developed on a selective number of satellite IR pictures. Pictures that portrayed ambiguous cloud boundary features could not used and are not part of the scatter diagram of Fig. 6.6. It is unknown how much different the relationship of Fig. 6.6 would be if all cloud pictures were utilized irrespective of cloud boundary utility.

Although the scatter of data points of Fig. 6.6 is large and the measurement of the mean extent of the typhoon's cloud shield can be difficult to make in many cases, these results nevertheless appear to offer the forecaster with some rational basis on which he/she might make a crude quantitative, or at worst, a qualitative estimate of a typhoon's outer circulation when other information is not available. This method might also be used in a checking or veryifying mode when other data are scarce or are of questionable quality.

It is unknown whether any alteration in this formula would be required for application in the other ocean basins. In that tropical cyclones are much the same in all ocean basins, we would expect this relationship should likely be generally valid everywhere.

This relationship is only to be applied to tropical cyclones of typhoon or tropical storm intensity. It is expected that the forecaster already will have had, or made, an estimate of the tropical cyclone's central pressure and maximum wind from aircraft or from the Dvorak (1975) scheme, and that he/she already has an estimate of the TC's speed and direction to make a right vs. left quadrant motion asymmetry correction.

Much more research is needed on this topic so that this initially measured relationship can be improved and qualified in the special cases where it is known or has been shown to be invalid. It is important that future research concentrate on the asymmetric aspects of the outer 30-

knot wind radius and the influence of different environmental circulation features on the increase or decrease of this wind radius.

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